Optimizing the structure of the natural gas market using an agent-based modeling framework

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Optimizing the structure of the natural gas market using an agent-based modeling framework

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Table of contents

1. Introduction

1.1 Energy policy

The availability of energy is crucial to the functioning of today's society. Mobility, communication, business and industry all depend on the input of large amounts of energy. By far the largest share of this energy is supplied by fossil fuels, of which oil, coal and natural gas are the three main types. Because of the importance of energy, governments all over the world have tried to influence and control their energy supply through energy policy. This section provides an introduction to the problem of energy policy optimization.

Over the last thirty years, the objective of energy policy has been threefold: to ensure the sustainability, security and affordability of energy supply. In other words, the production, delivery and consumption of energy should proceed without negatively affecting the environment or depleting its resources, consumers should be able to rely on an uninterrupted supply of energy, and energy should be provided efficiently and be priced accordingly. The difficulty in designing energy policy lies mainly in the fact that these three objectives are to some extent mutually exclusive. Furthering one objective often has to proceed at the cost of another, so there are tradeoffs involved between objectives (see Figure 1.1). The space occupied by the sphere in the figure signifies the policy space of policy makers. Each combination of policies can be assigned a point in this policy space, representing the degree to which each objective is fulfilled as a result of the sum total of energy policy in place. Any point on the surface of the sphere then belongs to the set of policy combinations which are optimal given a certain weighting of the different objectives.

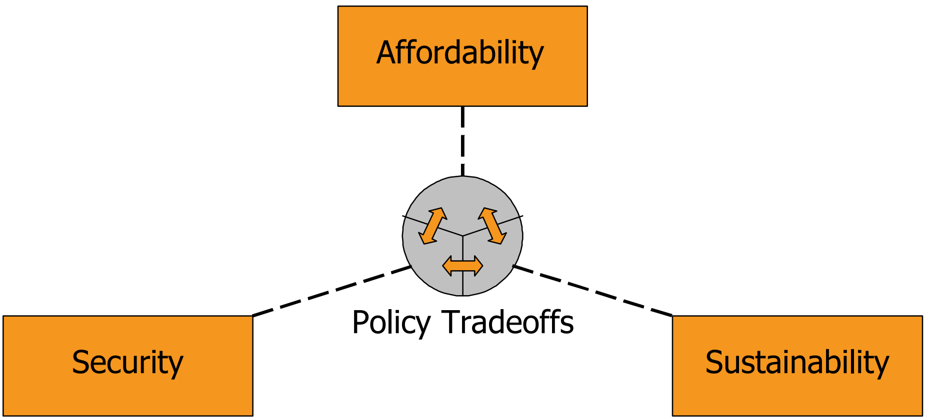


Figure 1.1: The objectives of energy policy can be mutually conflicting, in which case a tradeoff is necessary.

Any change in policy will cause a shift in the position occupied in or on the sphere. This means any change in policy can be justified in one of two ways. The first option is to argue that a policy change will further one (or more) of the objectives without negatively affecting others. In such a case, objectives are neutral or even complementary to each other. This is analogous to a move away from the centre and towards the surface of the sphere in the figure. The second option is to argue that, even though objectives are substitutes, the increase in utility gained from furthering one objective outweighs the loss of utility suffered from sacrificing another. This is analogous to a move along the surface of the sphere in the figure. In the first case, the relative weight attached to policy goals is irrelevant, but it is crucial in the second.

In the case of a tradeoff, the choice for one objective over the other has to be made by governments as a function of the perceived needs of society as a whole. To describe this phenomenon, Frei (2004) introduces a Maslow-inspired "energy policy needs pyramid" (see Figure 1.2). The objectives featured in the pyramid are similar to the three identified in Figure 1.1, but differ in a few respects. The main difference in classification is that sustainability has been split into three separate objectives: social acceptability, natural resources efficiency and access to commercial energy. Social acceptability can be understood as one country's efforts not to compromise the sustainability of other countries, as sustainability is a global rather than a national objective of a non-exclusive nature. Natural resources efficiency is normally viewed as a means to achieve sustainability rather than a goal in itself. Finally, access to commercial energy is a kind of mix between long term supply security and sustainability. It is a precondition to the other objectives, because without access to energy the other objectives make no sense.

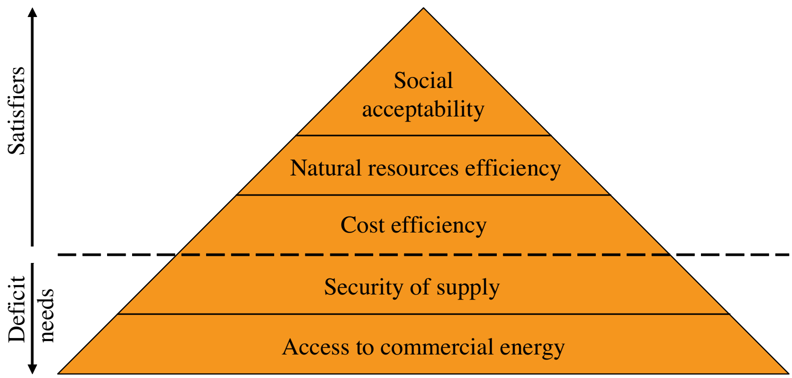


Figure 1.2: The energy policy needs pyramid, Frei (2004).

The pyramid acknowledges the fact that some objectives weigh more heavily than others. However, it suggests a rather all or nothing interpretation of policy tradeoffs, with objectives lower in the pyramid taking absolute precedence over those above them. In reality, the fulfillment of different policy objectives proceeds in parallel. Each objective is addressed by policy, but its degree of fulfillment is limited by the other objectives in the policy hierarchy. In other words, each objective is pursued to the extent that it is complementary with other objectives, and is pursued at the cost of others where the gains outweigh the losses.

Although in theory a unique policy optimum could be calculated, this is never done in practice. Performing a complete cost-benefit analysis is highly complex and the relative weight of each objective is under continuous political debate. In addition, the division of labor between policy makers means that each objective is pursued by a different political body with the required expertise in a specific area. For instance, in the case of energy policy, the ministry of the environment might pursue the objective of sustainability, while the ministry of foreign affairs pursues the objective of security and the ministry of economic affairs pursues the objective of affordability.

In such a situation, policy can be coordinated by providing each policy maker with a set of optimization constraints. This enables policy makers to focus on reaching their own objectives without negatively affecting others. As a consequence, the appropriateness of these constraints determines the quality of energy policy as a whole. Unfortunately, actual constraints imposed are often of a very general nature, merely stating that furthering one objective may not proceed at the cost of other objectives without specifying at which point this would occur. In other words, the issue of where complementarity ends and substitution begins, is not addressed. This means there is always a risk of policies negating instead of reinforcing each other.

The issue of pursuing objectives within the right constraints is an important theme in two branches of economics. Daly (2004) introduces the subject of ecological economics by contrasting it with neoclassical economics. Where neoclassical economics is concerned with the objective of allocative efficiency, ecological economics says allocative efficiency should only be maximized within the constraints of two other objectives: the optimal *scale* of the economy in relation to the surrounding ecosystem and the optimal *distribution* of natural resources, e.g. between current and future generations or between humans and other species. Similarly, new institutional economics provides a four-level characterization of social analysis, consisting (top-down) of society at large, the institutional environment, governance structures (as defined in transaction cost economics) and resource allocation, with higher levels constraining the optimization of the lower ones (Williamson, 2000).

In other words, both fields share the view that the neoclassical vision of the economy existing in a vacuum is incomplete, as the economy is in fact part of a greater system. Ecological economics concerns itself with the ecosystem as the particular greater system, and new institutional economics treats the economy as part of society. The two highest levels in the conceptual model of new institutional economics are called the institutional environment. The third and fourth level together form what is here called the economy, where the third level is associated with transaction cost economics and the fourth with neoclassical economics. These two views can be combined into a single conceptual model, in which society is a subsystem of the ecosystem and the economy is a subsystem of society. An important characteristic of a subsystem in this context is that it depends on the greater system it is a part of for its functioning. Therefore, the development of society is constrained by the ecosystem it is part of (i.e., its natural environment), and the development of the economy is constrained by both its institutional environment and its natural environment.

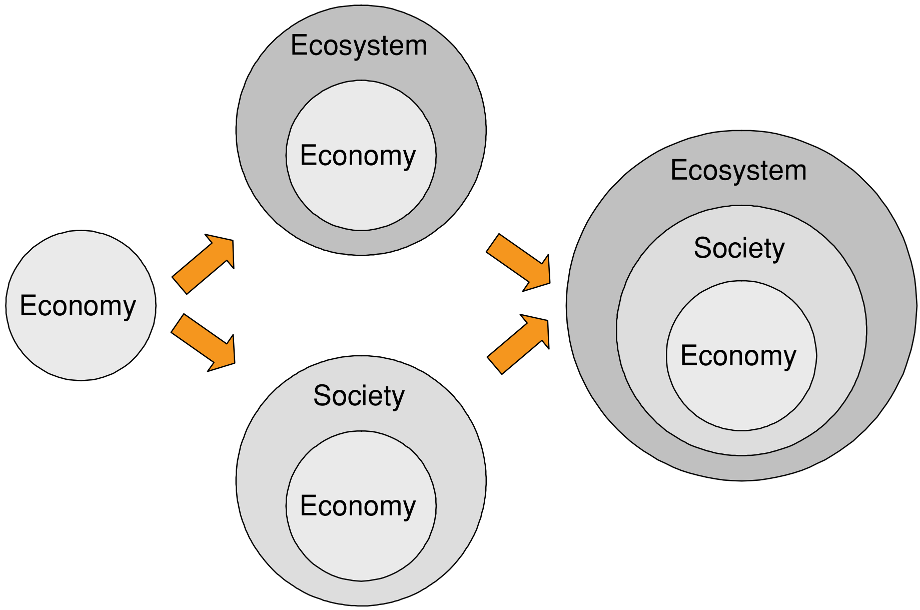


Figure 1.3: The views of ecological economics and institutional economics combined in a single conceptual model.

These insights are highly relevant to energy policy. As its three objectives suggest, energy policy must strike a balance between the performance of the economy, the wellbeing of society and the health of the ecosystem to arrive at an optimal set of policies. In the next section, natural gas policy will be examined in more detail from this perspective.

1.2 Natural gas policy

The natural gas life cycle can be fitted into the conceptual model identified in Section 1.1, with natural gas traversing the ecosystem, society and the economy (see Figure 1.4). The life cycle is split into five steps, starting with the formation of natural gas. Natural gas is formed in nature through the burial and transformation of organic materials. These processes take place on a timescale far larger than that of human civilization. Therefore, the amount of natural gas available in nature can be treated as a non-renewable, finite stock. However, the exact size of this stock is unknown for two reasons. First, not all natural gas available has been discovered, and second, the fraction of natural gas which is economically recoverable changes over time due to technological advances, changes in the price of natural gas and changes in the price of equipment and materials needed to recover natural gas.

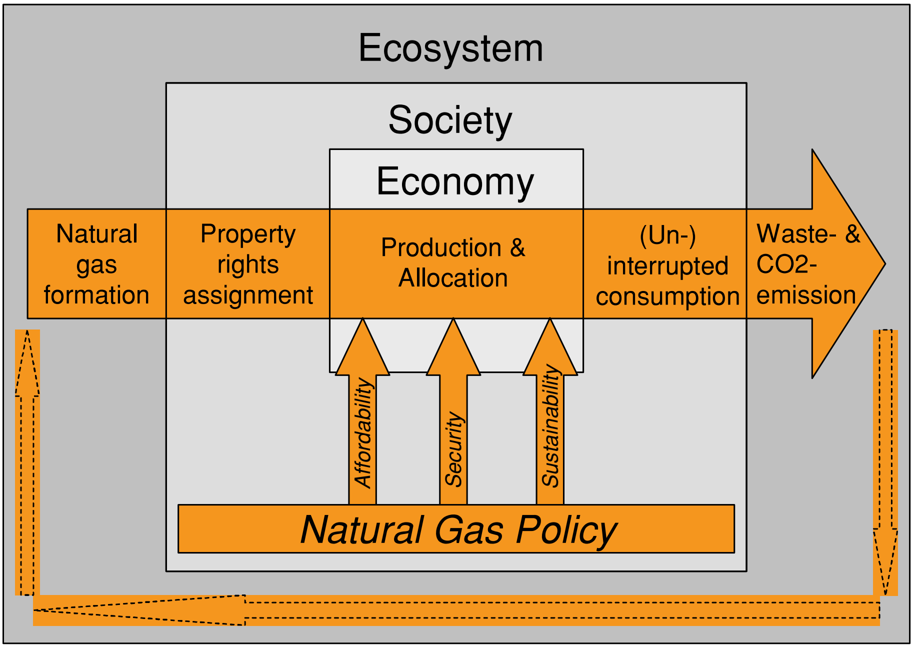


Figure 1.4: The three objectives of natural gas policy located within the domains of nature, society and economy.

Figure 1.4 also shows natural gas moving through society before it can enter the economy. This represents the fact that property rights are assigned to it before it is produced, processed and traded on the market. It also represents the fact that the natural gas market is subject to the rules and institutional arrangements society creates. Next, natural gas enters the economy, where it is determined how much is produced, at which price it is sold, and to whom it is allocated. Natural gas consumption is placed in the social rather than the economic system, characterizing it as an activity from which society gains utility. (For the purposes of this diagram, society consists of the citizens of a country and the government that acts on their behalf, whereas the economy consists of companies acting on their own behalf.) The level of supply security determines the frequency of supply interruptions. Finally, the byproducts of consumption, i.e. waste and CO_2, enter the ecosystem and may eventually be transformed into natural gas again.

Natural gas policy is an integral part of energy policy. It consists of policies directed at the natural gas market, aiming at the fulfillment of energy policy goals. Therefore, the shape which natural gas policy takes depends on a country's energy policy objectives and on the role which natural gas plays in its energy system. For instance, a country with large gas reserves will implement different policies from a country which is a large importer of natural gas. The diagram includes natural gas policy, which is conceptualized as the constraints society applies to the economy to reach its objectives. (The objectives of the economy itself are equated to the objectives of the companies that comprise it, which are to survive and be profitable.) Each policy objective requires a different set of policies to fulfill it, which may produce tradeoffs between objectives. With regard to the economic organization of the natural gas market, the main tradeoff to be made is between affordability and security. To show why this is so, the tradeoff between sustainability and the other two objectives will first be analyzed briefly.

The sustainability objective consists of two parts. The first is to avoid the depletion of the ecosystem's stock of natural resources, and the second is to limit the amount of waste and CO_2 produced by the consumption of energy to a level which can be safely absorbed by the ecosystem. Both parts of the objective require policies which span the whole energy sector for their fulfillment.

Achieving the first part of the objective, a truly sustainable supply of energy, implies the presence of an infinitely large stock of energy sources in the ecosystem. Since the stock of fossil fuels is finite, an energy system dependent on fossil fuels is ultimately unsustainable. Although an energy conservation program will lengthen the period of sufficiency, in the end the objective has to be achieved by realizing a transition from the use of finite resources to the use of non-finite resources such as wind energy, solar energy and biomass.

The second part of the objective requires similar policies, because fossil fuels are large emitters of waste and CO_2. Natural gas generates fewer harmful byproducts than oil and coal and is therefore considered to be the cleanest fossil fuel, but the CO_2-emissions associated with its consumption are still substantial. Limiting the damage to the ecosystem can be done in three ways. First, the use of fossil fuels can be reduced via a transition from CO_2-emitting fuels to cleaner energy sources such as wind energy, solar energy and biomass. Second, the demand for energy in general can be reduced. Third, the release of harmful substances into the ecosystem per unit of fossil fuel used can be reduced by e.g. the capture and storage of CO_2.

This means the sustainability objective can be pursued in roughly three ways: energy conservation, a transition towards clean and non-finite energy sources, and the adoption of 'clean carbon' technology. The effects of these policies on natural gas are mixed. Conservation policies will reduce the demand for natural gas, which has a positive effect on affordability and security, so there is no tradeoff involved. A transition to sustainable energy sources requires increasing the relative attractiveness of renewable sources compared to fossil fuels. When sustainable energy sources are promoted with subsidies, this does not affect the affordability and security of natural gas. However, when consumers are penalized for using fossil fuels by taxes or when companies must conform to environmental standards, this will affect the affordability of natural gas. In addition, since oil and coal are more polluting than natural gas, a transition from oil and coal to natural gas can also occur. Therefore, the net effect on natural gas demand will be small. Finally, the effect of clean carbon technology will be to increase the costs of natural gas use and thereby to reduce its affordability.

These policies have in common that they do not interfere much with the economic organization of the natural gas market. Conservation policy is directed at the consumer, whereas the relative attractiveness of different fuels can be changed with the help of taxes, subsidies and environmental standards. This produces a clear tradeoff for policy makers: sustainability can be promoted at the cost of affordability, without intruding deeply into the structure of the natural gas market.

In contrast, policies aiming at the affordability and security of natural gas supply often have a large impact on the structure of the market. The best example of such a high impact policy is the process of liberalization, which has radically changed the structure of natural gas markets over the last two decades. As a consequence, the main concerns of natural gas policy are affordability and security.

It should be noted at this point that there is another objective commonly subsumed under natural gas policy, which is a country's goal to maximize its resource rents. This study's conceptual model treats the objective differently. As resource rent maximization does not add to the quality of society's energy supply, it is not considered a separate objective of society. It is treated as part of the economy instead, where the owner of a natural resource can display profit maximizing behavior. In the case of a country rich in natural gas, it is clear that there is a tradeoff to be made between affordability and resource rent maximization. In such a situation, a country's objective to maximize its resource rents is treated as an additional constraint to the affordability objective.

1.3 Natural gas policy after liberalization: hierarchical optimization

Society has two basic ways of reaching its policy objectives via the economy. The first is to become a player in the market itself by creating a publicly owned company. The second is to create a set of rules and institutions (i.e. an institutional environment) to govern the market which provides private companies with the right incentives to fulfill society's objectives. In the European Union, liberalization constituted a move from the first to the second method (see Chapter 2 for a more detailed description).

This indirect method for achieving society's objectives can be analyzed with the concept of hierarchical optimization, where optimization on one (in this case: social) level is performed by providing constraints to the optimization processes at a lower (in this case: corporate) level. This concept is represented graphically in Figure 1.5. Each level's optimization constraints are shown on the left and each level's optimization criteria are shown on the right. The arrows signify that the constraints cascade downwards (i.e., constraints on one level are determined at the level above it), whereas optimization criteria cascade upwards (i.e., the outcome of an optimization at one level is determined by the optimization at the level below it).

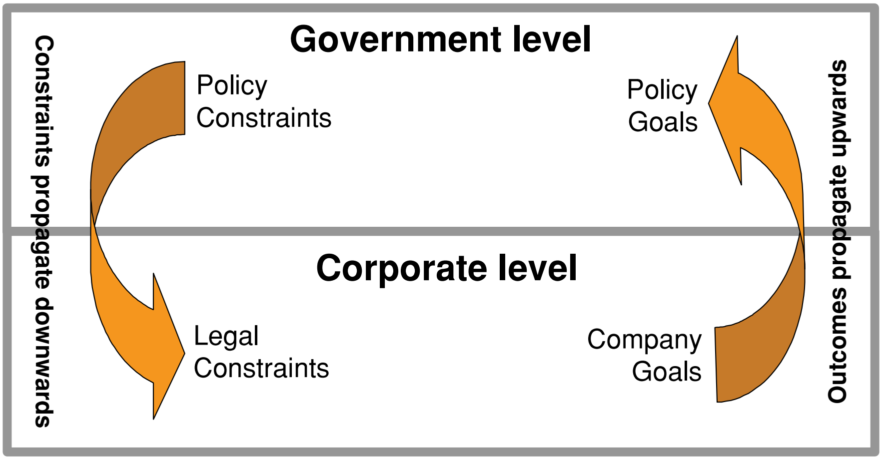


Figure 1.5: The principle of hierarchical optimization.

Security and affordability are both objectives of energy policy. However, mathematics tells us that it is impossible to optimize a system with regard to two objectives simultaneously. In the case of multiple goals, they can either be merged into a single goal by assigning them a relative weight or they can be differentiated by treating one as the optimization goal and the other as an optimization constraint. A third option is to optimize both separately, but this provides no guarantee of an optimal outcome. As outlined in Section 1.1, actual government behavior is somewhere in between the second and the third option. In most European natural gas markets, the pursuit of the affordability goal has been assigned to a regulatory authority. Although the regulatory authority is notionally constrained in its actions by the requirement not to harm supply security, little has been done to translate this general requirement into concrete recommendations. In this study, the hierarchical optimization concept is used to study the process of affordability maximization within the constraint of supply security. This regulatory process is represented as a hierarchical optimization problem in Figure 1.6.

It should be noted that although supply security is treated as a constraint with regard to governing the economy, it can still be treated as an objective on a political level. In contrast to affordability, supply security has both a political and an economic dimension (see Chapter 2). As a consequence, it can be optimized at a political level by e.g. building stable political relations with producing countries, and at the same time function as a constraint to the hierarchical optimization process being applied to the economy. In other words, affordability and supply security can both be maximized, but through different optimization processes, and only to the extent that they are complementary to each other.

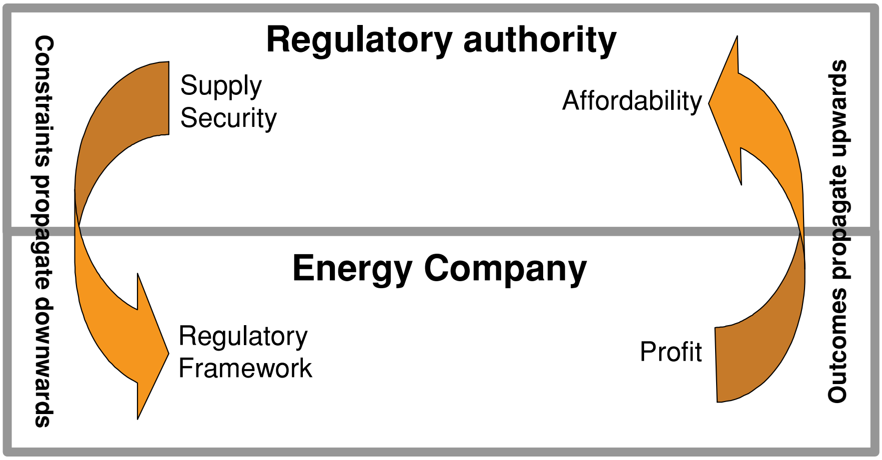


Figure 1.6: The hierarchical optimization process applied to the natural gas market.

It should also be noted that, to be complete, a third level should be added to Figures 1.5 and 1.6 on top of the other two. This top level would consist of the ecosystem, which constrains society with regard to e.g. the availability of natural resources. In addition, the health of the ecosystem is a function of society's behavior, i.e. its depletion of natural resources and its emission of pollutants.

Using this conceptual model, each individual policy implemented by a regulatory authority can be analyzed in three steps. First, a policy can be translated into a set of constraints posed to energy companies. Second, the changes these constraints induce in the behavior of companies can be derived. Third, the effect of the combined behavior of all energy companies on affordability and supply security can be analyzed. Following this procedure ensures that the effects of a policy on both goals are identified, which is a prerequisite for optimizing policy. It will be shown in Chapter 3 that the apparatus to perform such an analysis is currently lacking. Therefore, the bulk of this study will be concerned with the development of such an apparatus. Only after a modeling framework has been developed will attention be turned to the actual analysis of natural gas policy.

1.4 Objective of the study and research questions

The objective of this study is twofold. Its first objective is to develop a quantitative framework in which it is possible to systematically analyze the hierarchical optimization problem of natural gas policy described above, with affordability as its goal and a degree of supply security as a constraint. Its second objective is to use this framework to analyze the effects of liberalization and the regulatory control activity following from it on affordability and supply security.

Therefore, the overall research question guiding this study is the following: what is the optimal structure of the natural gas market, considering both the degrees of affordability and supply security resulting from this structure? While a definitive answer to this question is beyond the grasp of this study, it serves as an ultimate aim which is approached gradually by subsequently answering five sub-questions.

These sub-questions are:

1. How can the concepts of supply security and affordability be usefully defined? (Chapter 2)
2. What should a modeling framework for analyzing the natural gas market with regard to these concepts look like? (Chapters 3 and 4)
3. What general conclusions can be drawn on the basis of this framework? (Chapter 5)
4. What is the effect of liberalization on the Dutch natural gas market? (Chapter 6)
5. What are the possible effects of current trends unfolding in the Dutch natural gas market? (Chapter 7)

The framework constructed in this study implicitly contains the necessary elements for deriving a sustainability indicator too. However, to limit the scope of the study, sustainability will not be analyzed explicitly.

1.5 Thesis outline

Chapter 2 provides an introductory description of the natural gas market. Starting from a description of the natural gas value chain, the process of liberalization is described as a change in the organization of the value chain. In addition, the concepts of affordability and supply security are discussed and appropriate quantitative indicators for both objectives are identified.

In Chapter 3, a survey of existing gas market models is performed. On the basis of this survey, a classification system for natural gas market models is developed. Furthermore, the characteristics of a modeling framework fit for the purpose of this study are derived.

In Chapter 4, a general, quantitative framework for natural gas market modeling is developed on the basis of agent-based computational economics. The model's structure, its dynamics, output and data requirements are described. Furthermore, the properties of each agent are explored, and the possibilities for model verification and validation are outlined.

Chapter 5 provides a number of applications of the modeling framework. It contains a series of seven increasingly complex models, detailing the functionality of the modeling framework. Some general conclusions are drawn based on these models. In addition, the possibilities of using the framework as a tool for educational gaming are explained.

In Chapter 6, two models of the Dutch natural gas market are developed, one of which corresponds to the pre-liberalization structure of the Dutch market and one to its post-liberalization structure. The performance of both models is then compared to assess the impact of liberalization on the Dutch market.

In Chapter 7, the post-liberalization model of the Dutch natural gas market is used to perform a scenario study, in which three trends are extrapolated to the future and their impacts are studied. These trends are the transition to a sustainable energy system, the integration of the Dutch market within a single European market, and the behavioral changes induced by the liberalized market.

Finally, Chapter 8 summarizes the previous chapters and provides some overall conclusions and recommendations regarding the design and implementation of natural gas policy. The study ends with some ideas for the further development of the modeling framework.

2. A conceptual framework for analyzing the natural gas market

2.1 The natural gas value chain

"The natural gas market" is a broad term generally denoting the economic organization of all activity pertaining to the sale of natural gas. Underneath this organization lies a series of processes which remain constant throughout any organizational changes taking place in the natural gas market. These processes together can be called the natural gas value chain, which is a sequential ordering of all activities adding value to the natural resource which is the basis of the value chain. The natural gas value chain can best be described by distinguishing 7 processes: exploration, production, processing, transport, storage, distribution, consumption. This is shown in Figure 2.1. Each process is described briefly below.

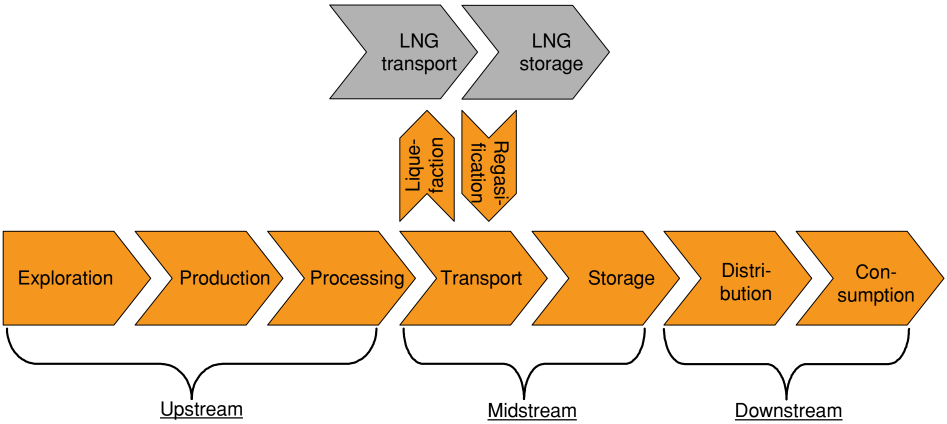


Figure 2.1: The natural gas value chain.

The first step in the value chain is exploration. This entails analyzing the subsurface, drilling exploration holes and identifying the characteristics of natural gas reservoirs. The second step is production, which consists of the development and management of production infrastructure and the actual transport of natural gas from the reservoir to the surface. After gas is produced, and before it can enter the main transportation networks, it often requires processing. This means removing impurities from the gas and possibly mixing it with other gases to achieve the right calorific value. After processing, the gas can be treated as a commodity. Exploration, production and processing are often treated as a single process and referred to as "upstream" or E&P.

The next step in the chain is transportation, which means transporting natural gas from the location of production through a pipeline to the location of consumption (in the case of large consumers), distribution (in the case of small consumers), or storage.

In the case of storage, natural gas is injected into a storage facility. A storage facility can be a depleted gas field, a salt cavern, or an aquifer. It is stored in the facility until it is needed and is then produced from the facility and transported again to the location of distribution or consumption. Transport and storage are together referred to as "midstream".

Optionally, natural gas is then transported through a distribution network before it arrives at the location of consumption. Distribution takes place through smaller, lower-pressured, more branched networks than transport. It is used to supply natural gas to households, offices and other small users. Finally, natural gas is consumed. It can be burnt for space heating, cooking and electricity generation or used as an input for chemical processes. Distribution and consumption are referred to as "downstream".

LNG (Liquefied Natural Gas) occupies a special position in the value chain. Natural gas can be turned into LNG through the process of liquefaction. The reverse process of turning LNG into natural gas is called regasification. When in a liquid state, the gas can be transported using LNG-ships and/or stored in an LNG storage facility. As such, it is part of the midstream, although for regulatory purposes it is sometimes treated as part of the upstream.
The 7 processes described above are organized into "the natural gas market" by means of governance structures which connect them. Governance structures are usually classified into three types: contracts, hierarchy and markets (Williamson, 1975). Both the type of governance structure used and the degree of government involvement in each part of the value chain have changed significantly with the advent of liberalization. The pre- and post-liberalization market structures are discussed further in Sections 2.2 and 2.3 respectively.

2.2 Structure of the natural gas market – pre-liberalization

There is no such thing as 'the' pre-liberalization market structure for natural gas, because the term "liberalization" has meant different things in different times and places. To prevent confusion, the scope of this research is limited to the liberalization process in the European Union (EU). Furthermore, even within the EU the liberalization process is very different from country to country. Therefore, the pre- and post-liberalization structures described in this section and the next are necessarily ideal types.

Nevertheless, it is possible to make some useful generalizations about these structures, because the actual market structures of EU countries are invariably a mixture of the ideal types presented here. The pre-liberalization structure comprises a set of values for a number of elements which together determine market structure and the post-liberalization structure comprises a different set of values for the same elements. Each actual market structure can therefore be described by a value for each element which is somewhere in between the ideal types sketched below (see Figure 2.2).

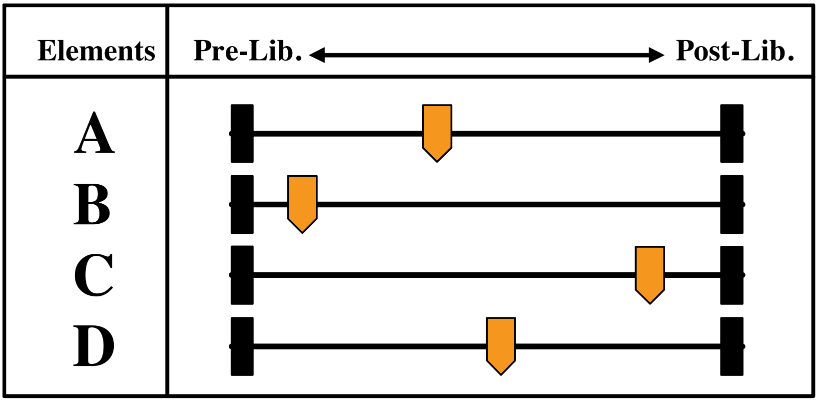


Figure 2.2: Each actual market structure is a combination of pre- and post-liberalization elements.

The pre-liberalization structure can be described by the following characteristics:

- Upstream: the government owns a country's natural resources. It licenses operators to explore the subsurface and produce the resources found. There is a mining law in place which governs the exploration and production process. A public company is either a partner of private, multinational E&P companies or the sole operator. Exploration, production and processing are integrated into a single company through a hierarchic governance structure. Sometimes, these companies also operate storage facilities to gain some flexibility in production. Upstream is connected to midstream through long term contracts, which contain price and quantity specifications. In the case of countries which do not have their own natural gas resources, long term contracts are closed with foreign upstream companies.
- Midstream: the midstream is dominated by large, government owned companies with a monopoly in transport and supply to consumers. They receive gas from long term contracts, transport it through their network and sell it to distribution companies and large consumers. If necessary, they also operate storage facilities to balance supply and demand. Midstream is connected to downstream by contracts, which contain price and quantity specifications. In general, these contracts have a shorter duration than the upstream-midstream contracts.
- Downstream: the organization of the downstream segment is similar to the midstream segment. Regional monopolies owned by local government operate distribution grids and sell to the consumers on the network. Again, these companies have a statutory monopoly with regard to transport and supply.

2.3 Structure of the natural gas market – post-liberalization

The post-liberalization structure differs from the pre-liberalization structure in the following ways:

- Unbundling: the process of unbundling constitutes a shift in governance structures from hierarchy and long term contracts to short term contracts and/or markets. The formerly integrated functions of transport, storage and supply (to large consumers and distribution companies) are separated, as are the formerly integrated functions of distribution and supply to small consumers. A minimal form of unbundling is to separate accounting (accounting unbundling), but in most cases the management of each function is also separated (management unbundling) and separate legal entities are created for each function (legal unbundling). The most complete form of unbundling is to separate ownership too (ownership unbundling), but this type of unbundling is still heavily debated. In addition, a spot market is founded to facilitate trade in natural gas between the different suppliers which are now in competition with each other. In cases where a spot market is not feasible and contracts are therefore unavoidable, the length of the contract is minimized and secondary markets for these contracts are stimulated.
- Competition and TPA: statutory monopolies are abolished. Therefore, all parts of the supply chain are open to competition. This also means that consumers are no longer captive, but can choose their supplier. Those parts of the chain which constitute natural monopolies, mainly transport, are regulated to avoid the abuse of a dominant position. This regulation consists of price caps and third party access (TPA). Although TPA follows automatically from unbundling, regulation is developed to make sure the TPA is applied indiscriminately. A distinction is made between negotiated TPA, where the terms of access are left to be determined by negotiating parties themselves, and regulated TPA, where a single access regime applies to all parties and is co-designed or approved by the regulator.
- Government role: the role of the government changes from participating in the market as a shareholder, to being the regulator of the market. This is achieved through the privatization of public companies, the creation of a gas law, and the creation of a semi-independent regulatory authority.

2.4 Affordability, competitiveness and economic efficiency

As explained in the previous chapter, the goal of this study is to assess the performance of the pre- and post-liberalization market structures with regard to affordability and supply security. To do so requires the use of indicators for both objectives. In the case of affordability, using price as an indicator would seem the obvious choice. However, matters are complicated by the recurrent use in the literature of two other terms, competitiveness and (economic) efficiency, which are almost, but not quite, interchangeable with affordability. The term competitiveness is often used in policy documents, whereas the term efficiency is most prevalent in academic articles.

Competitiveness, or “to be competitive” originally meant being in competition. However, in recent years a second meaning has become increasingly common. This meaning is “the ability to compete”, which has a clear positive connotation (George, 2008). Applied to the natural gas industry, this means that its competitiveness can either be measured by the degree of competition in the industry or by its performance relative to other industries. In the first case, competitiveness takes on a meaning different from affordability. In the second case, competitiveness has the same meaning as affordability only if the measurement of performance is limited to its price component. If performance includes other aspects as well, the term competitiveness becomes more diffuse. Policy makers often treat the term as if one meaning implies the other, i.e., as if increasing competition necessarily increases performance. As this does not always hold true, the use of the term affordability is preferable from an energy policy perspective. After all, society does not benefit from competition per se, but only from its possible positive consequences.

The term efficiency has a more solid grounding in economic science. Efficiency can be differentiated into static and dynamic efficiency. In the static approach, market outcomes are evaluated at a single moment in time. Efficiency is measured by the total utility gained from all transactions at that moment. The main determinants of utility are the quantity of goods sold, their price, and the allocation of goods to consumers. Maximum efficiency is attained when such an amount of goods is produced that all consumers willing to pay at least the cost of production are served. In the case of a perfectly price discriminating monopolist, all the surplus accrues to the producer, whereas in the case of a competitive market, all surplus accrues to the consumer. Interestingly, liberalization entailed a move from one (quasi-)efficient market configuration to another. Before liberalization, most suppliers qualified as price-discriminating monopolists, whereas the end goal of the EU is a competitive market.

According to the structure-conduct-performance paradigm, the producer’s conduct is determined by the structure of the market, which makes market structure the ultimate determinant of static efficiency. However, in the absence of price discrimination, the price-to-cost ratio can be used as a proxy for static efficiency. When price moves closer to cost, the combined utility of consumer and producer will increase, and so will the consumer’s share of utility (see Figure 2.3). Therefore, when costs are assumed constant, price can serve as an indicator equally well, and becomes a proxy for static efficiency.

Dynamic efficiency emphasizes the improvement of market outcomes over time, rather than focusing on particular market outcomes. From the dynamic perspective, innovation combined with creative destruction is the main source of increases in efficiency. Therefore, efficiency is not a function of market structure, but is the result of a continuous process of discovery. The indeterminate nature of this process means that dynamic efficiency is seldom quantified. Possible quantitative indicators are cost reductions (due to process innovation) and the number of new products entering the market (due to product innovation). Similarly, the price-to-cost ratio is not inversely correlated to efficiency. Rather, a high price-to-cost ratio is a necessary reward to innovators. Its absence would make innovation unprofitable and stagnation would ensue. However, even with a high price-to-cost ratio, cost reductions will drive down prices, which means increases in dynamic efficiency will translate into price decreases over time.

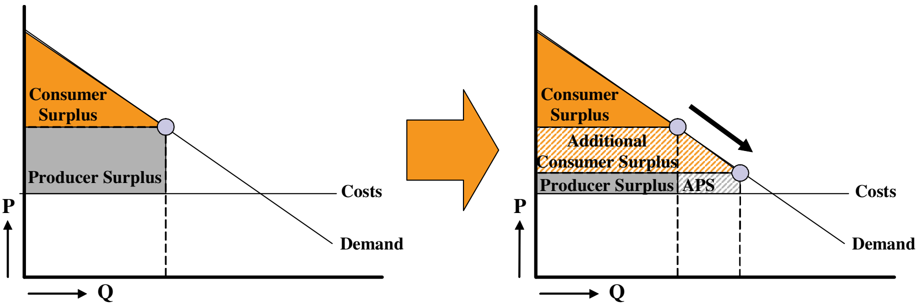


Figure 2.3: An increase in static efficiency.

The difference between the static and dynamic perspective with regard to the design of energy policy is made apparent by Robinson (2000). In his discussion of economic liberalism, he identifies both schools of thought and shows that government interventions in the energy market are mostly based on static efficiency arguments and aim at creating an optimal market structure. As a proponent of the dynamic perspective, Robinson argues that such interventions are unwarranted, because the optimal market structure changes continuously as a result of the ongoing competitive process.

In summary, the concept of affordability is related to competitiveness and efficiency, but not identical to them. Whereas the term competitiveness suffers from ambiguity and has no clear correlation with affordability, static and dynamic efficiency can both be approximated by using price as an indicator. Therefore, in this study, “price” will be adopted as an indicator of affordability. This leaves open the question of *which* price should be used as an indicator, but this question will be dealt with in later chapters.

2.5 The relevance of supply security to the natural gas market

Whereas affordability is deemed important in virtually any product market, security of supply is only considered an issue in a few specific markets. These are usually markets for life’s necessities, such as food, water and energy. There are several reasons why supply security is especially important for the natural gas market. This section provides a summary of why this is so.

In the new millennium, several incidents have highlighted the possible risks to a secure gas supply. The California crisis showed the danger of flawed market design.

The recent problems between Russia and the Ukraine have highlighted the risk of the use of gas as a political weapon. And the British gas balancing alert in the winter of 2006 has shown the risks attached to an essential facility breakdown. Other developments such as the depletion of indigenous gas sources, the European internal market and plans for emission reduction have a more subtle effect on the security of supply.

The importance attached to supply security is visible in policy related literature. Policy reports on the subject have been issued on a national, European and global level and many articles have addressed the subject of energy security from a policy perspective. Recent examples include Bielecki (2002), Salameh (2003) and Li (2005). The reason for the relevance of the supply security issue to natural gas is twofold. First, natural gas supply is more vulnerable to disruption than the supply of most other commodities. Second, the consequences of a disruption are greater.

The reasons for the vulnerability of natural gas supply lie in a combination of the properties of both demand and supply. An overview of those properties is provided below.

- Most consumers use natural gas for purposes that are essential to their functioning, such as electricity generation, space heating, and fueling industrial processes. Therefore, the demand for natural gas is highly inelastic. In other words, it takes an enormous price rise to convince a consumer to stop using natural gas. In addition, as heating is a significant portion of consumption, demand for natural gas is highly seasonal. This means demand exhibits natural fluctuations throughout the year.
- Natural gas is a natural resource. Finding natural gas and setting up production is a complex, expensive and time consuming process, which means projects have long lead times. Because of limited knowledge about the subsurface, producers do not know in advance how much they will find. Nor is it possible to find natural gas everywhere. Occurrences of natural gas are distributed over the world highly unequally. This means geological features constrain the behavior of producers in several important ways.
- As a natural resource, natural gas is owned by governments. Many companies are partially or wholly controlled by the state, and this adds a political dimension to the exploration for and production of natural gas. A state company's behavior is more complex than that of a purely commercial company, as commercial goals may be made subservient to political goals.
- Under standard conditions, natural gas is in a gaseous state. Therefore, it is not delivered in discrete portions but as a continuous flow through dedicated pipelines. To maintain sufficient pressure in those pipelines for the gas to flow smoothly, gas that exits the pipeline must be replaced quickly. If this does not happen, pressure will drop and delivery to all consumers dependent on that pipeline is jeopardized.
- The natural gas industry is and has been for many years subject to an extensive reform process. This has greatly increased uncertainty for companies in the

natural gas industry about its future, as well as introducing many untested mechanisms for organizing the different steps in the value chain.

Summarizing, natural gas supply is vulnerable because of fluctuating but inelastic demand, limited control over timing, quantity and location of production, the possibility of political interference, technical constraints on delivery and continuous regulatory experimentation.

If the properties of natural gas supply mentioned above should cause a disruption, the consequences would be severe. In the case of a prolonged shortage of natural gas, the whole economy could come to a standstill, as virtually all sectors depend on sufficient energy for their functioning. In the case of a cold winter, a lack of heating could also cause hardship for households. This being said, even a short disruption would inflict serious economic damage. Many industries depend on natural gas supply to such an extent that factories would be heavily damaged in the event of an interruption. A lack of natural gas for electricity generation could cause an electricity outing, with its own economic consequences. Finally, a disruption of natural gas supply to small consumers could necessitate a door-by-door reconnection to the grid to prevent safety hazards, which would be a highly expensive operation.

2.6 A quantitative definition of supply security

"Security of supply" is an ambiguous term. It refers to the availability of supply in sufficient quantity at a reasonable price, but the words "sufficient" and "reasonable" often remain vague. As discussed in Section 1.3, supply security will be treated as an optimization constraint in this study. Therefore, it is necessary to define quantitatively under which conditions supply is considered secure. From this perspective, the concepts of sufficient quantity and reasonable price can be translated into such conditions.

Supply will be considered secure if at all times demand is equal to (or smaller than) supply at a price equal to or smaller than P_{max}. This is illustrated in Figure 2.4. In situation A (with demand curve D1), the market clears at a price below P_{max}, so the supply security constraints are met. However, if demand curve D1 is replaced by curve D2, the market arrives at either situation B or C. In situation B, a price cap prevents the market from clearing, so demand is greater than supply. In situation C, the price constraint is relaxed and the market clears at a price higher than P_{max}. From the perspective of supply security, both situations B and C are unwanted. It should be noted that, even without a price constraint, a shift from D1 to D2 may breach security if the supply adjustment process from A to C is too slow.

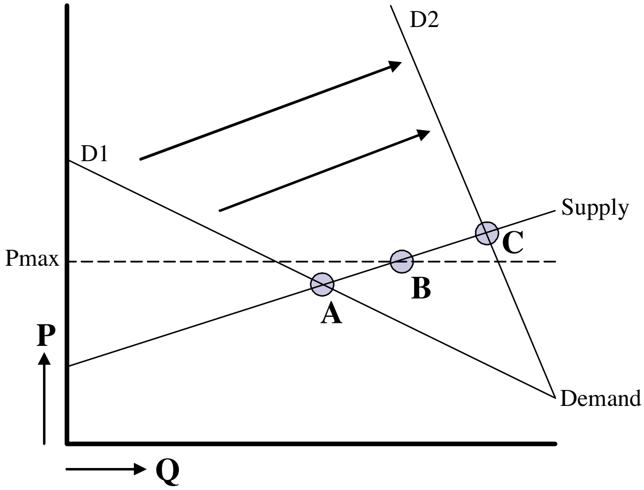


Figure 2.4: The constraints posed to the market by the supply security objective.

An additional constraint which cannot be incorporated in a purely economic diagram is that physical flows should be in line with economic outcomes. For example, if a consumer buys natural gas on the market but the commodity is not delivered to its house on time, supply security will be breached even though the former constraints are not violated.

Therefore, three conditions must be satisfied for supply to be secure: the quantity condition (Eq. 2.1), the physical condition (Eq. 2.2) and the price condition (Eq. 2.3).

$$D \leq S_C \tag{2.1}$$

$$S_D = S_C \tag{2.2}$$

$$P \leq P_{\max} \tag{2.3}$$

With:

D	=	End-user demand
S_C	=	Supply contracted by end-users
S_D	=	Supply physically delivered to end-users
P	=	Price
P_{max}	=	Maximum acceptable price

From this perspective, security policy should aim at structuring the market in such a way that these security conditions are met continuously. However, another way to conceptualize security is to view it as providing insurance against the risk of supply interruption. Furthermore, it is often assumed that under 'normal' circumstances supply security will not be an issue, but only when certain specific risks arise. Several studies into the subject therefore take the form of identifying risks to security and discussing possible ways to guard against those risks.

NERA (2002) provides a quantitative definition of optimal security from this perspective, describing it as the level of security where the cost of providing an additional unit of security is equal to the consumer's willingness to pay for an additional unit. This definition bears a close resemblance to the affordability-security tradeoff identified in Chapter 1. It acknowledges that having 100% security may be suboptimal for natural gas policy as a whole. However, NERA also acknowledges that both variables in the definition are difficult to estimate, which makes this definition rather impractical for use by policy makers. For the power sector, extensive research has been performed to estimate the value of lost load (De Nooij et al., 2007), which is similar to the consumer's willingness to pay for security. However, such data are currently lacking for the natural gas sector.

An initial, qualitative classification of security risks was made by the International Energy Agency (1995). Three categories of risk were identified: 1) the technical risk of a supply facility being put out of action, 2) the failure to mobilize long-term supply or ensure long term deliverability of that supply, 3) the risk of political events causing a disruption to existing supplies or preventing new supplies from being mobilized. Later studies focused on the effects of liberalization on security of supply. Some regard it mainly as an opportunity for enhancing security (International Energy Agency, 2004), while others emphasize the risks created by flawed market design (Jepma, 2004) as well as the reduced power of governments to counter those risks (Wright, 2005). Finally, Stern (2004) proposes a quantitative approach to the analysis of supply security, which consists of identifying the risks to supply, the costs of guarding against those risks and the allocation of risks and costs to actors in the industry.

The concept of insurance against specific security risks will also be adopted in this study, but all risks previously identified will be regrouped into two main categories: risks *internal* and *external* to the economic system under consideration. Internal risk is defined as the risk to supply arising from the structure of the natural gas market. For this purpose, regulation is considered to be internal to the economic system, as it is fully controllable by policy makers. Internal risk can be further subdivided into short term and long term risk. Short term risk is determined by the static structure of the system, i.e. a structure in which certain changes are disregarded as they take place on a time scale greater than the time scale on which the analysis takes place. Long term risk is determined by the dynamic structure of the system, i.e. the velocity and direction of changes in system structure. More specifically, this can entail investment in new facilities, regulatory changes and changes in governance structures.

External risk is defined as the risk arising from events that have their cause and origin outside of the economic system. External risk is subdivided into three categories:

political, facility and weather risk. Political risk is the risk of interference with the functioning of the natural gas market for political purposes. Facility risk is the risk of a facility breakdown. Finally, weather risk is the risk of an extremely cold winter which raises demand to unusually high levels. The location of internal and external risks in system and environment is shown in Figure 2.5.

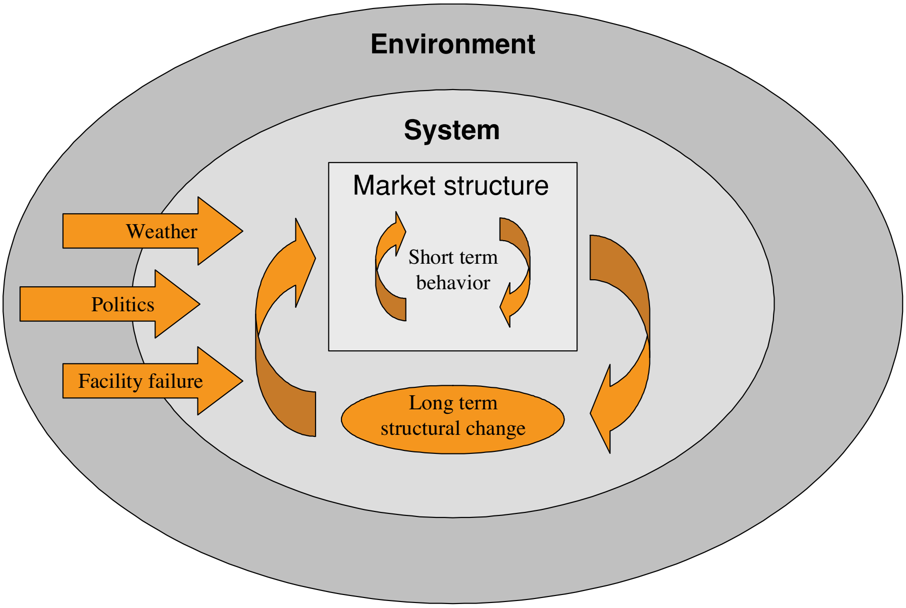


Figure 2.5: A classification of security risks.

In the context of risk management, supply security can be quantified as the probability of meeting the conditions for secure supply. In general, external risk depends on the probability of an external event occurring. In the case of weather risk, for example, the probability of a certain temperature occurring will be an input to the model. Internal risk, on the other hand, does not depend on external events, so the outcome is deterministic. This being said, the outcome can be made probabilistic by adding a probability distribution to other system inputs such as demand elasticity, the state of the subsurface and the attitude to risk of market parties. The five categories identified are described in more detail below.

<u>Short term internal risk</u>: in recent years, natural gas markets have witnessed problems that were caused by the new structure of the market. In the case of California, some companies found ways to make additional profits by creating artificial scarcity, which sent prices soaring and disrupted supply. In principle, short term internal risk is an all-or-nothing risk. The design of the market is either adequate, in which case supply is

secure, or the design of the market is flawed, in which case problems will almost certainly occur. However, it is possible that a certain level of demand is necessary to 'trigger' the problem. It may therefore be necessary to quantify such thresholds in addition to identifying the relevant disruptive market mechanism.

<u>Long term internal risk</u>: The long term phenomenon which has attracted the most attention in recent years is the adequacy of investment. The maintenance and possible expansion of supply capacity and available volumes of gas requires many types of investment, the most important ones being investment in exploration, production capacity, transport capacity and storage capacity. If, for some reason, the amount of investment is insufficient, a mismatch will occur between demand and supply. To analyze this risk, two processes are of particular interest: the long term development of demand levels and the rates of investment in different parts of the supply chain. In particular, investment decision processes should be modeled in detail.

<u>External weather risk</u>: When demand reaches a sufficiently high level, physical infrastructure will be unable to deliver the amount demanded. This could happen in a very cold winter, when the use of natural gas for space heating reaches extremely high levels. The level of demand at which infrastructure is no longer adequate has traditionally been quantified by means of a peak day and a peak winter. Demand is considered to be an inverse function of temperature and the level of security is expressed as the frequency of a fatal temperature occurring. This category is commonly subdivided into a peak day and a peak winter. On a peak day, production and/or transport capacity are insufficient. In a peak winter, the volume of gas available is insufficient. For example, the security of supply could be at the level of a 1-in-20 peak day and a 1-in-50 peak winter, in which case capacity would be insufficient once every 20 years and the available volume would be insufficient once every 50 years. In a liberalized market with multiple infrastructure users, the problem may not only be one of physical shortage, but also one of suboptimal allocation of the right to use the infrastructure.

<u>External facility risk</u>: This term refers to production, transport and/or storage facilities going offline for a certain period. This could occur because of internal malfunctioning, acts of terrorism, or extreme weather. Although a facility is part of the natural gas market, the cause of its breakdown is assumed to lie outside of the system and therefore it is treated as an external risk. The influence of the system on the probability of a breakdown occurring (e.g., in the case of insufficient maintenance increasing the probability) is not considered in this study. If other parts of the supply chain cannot compensate for a breakdown, security is breached. The quantification procedure described for external weather risk can be applied here with some modifications. Instead of temperature, the main inputs are which facilities go offline at which time and for which period of time.

External political risk: The possibility of a deliberate interruption of the supply and/or transport of gas for political gain, is labeled a political risk. Although the effect of such a disruption is similar to that of a facility failure, both its causes and the reactions of governments and market players it induces are very different. This difference can be incorporated by using different probabilities of interruption and by assuming different types of behavior by market participants in the case of an interruption.

In addition to analyzing these individual risks, a system can be subjected to multiple risks at the same time, in which case risks may either amplify or counteract each other. This will provide a more complete picture of the security level of a given economic system.

In the next chapter, a survey of existing models is performed with the purpose of determining the required characteristics of a model with which to quantitatively analyze the natural gas market with regard to affordability and supply security.

3. Modeling the natural gas market

3.1 A survey of natural gas market models

Over the last twenty years, a small but significant number of natural gas market models have been developed. Most of these models were concerned with the efficiency of natural gas supply. They have in common a static interpretation of economic efficiency, which determined model structure to a large extent. In this chapter, a systematic approach is taken to determining the requirements of a model which is to be used for studying affordability and security simultaneously. In this section, a survey of existing models is performed. The dominant modeling tradition is reviewed, its limitations are discussed and an alternative is proposed. In Section 3.2, the relevant issues for gas market modeling are identified. Issues which are related are grouped into a modeling dimension, yielding three dimensions in total. This allows all existing models to be assigned a position in three-dimensional modeling space, which is done in Section 3.3. Finally, in Section 3.4, this classification system is utilized to derive some hypotheses about the required characteristics of a model fit for purpose. The model proposed can then also be assigned a position in modeling space.

The majority of existing gas market models is based on a single method, here referred to as 'market equilibrium modeling'. In this section, its characteristics and shortcomings are reviewed, some models that deviate from this approach are discussed and, finally, dynamic system modeling is introduced as an alternative.

The survey was conducted by performing an extensive scan of model descriptions published in the period from 1995 to 2008, and by means of discussions with market parties about their own - confidential - natural gas market models. The main criterion for including a model in the survey was whether or not it represented the whole value chain. However, in a few instances partial models are discussed that display a useful characteristic not found in integral models. No comprehensive review of natural gas market modeling was found to exist, but some partial reviews are referred to. Smeers (1997) and Bunn and Dyner (1996) each provide a methodological overview of a certain modeling approach, whereas Ventosa et al. (2005) review some trends in electricity market modeling.

Smeers' (1997) overview of computable equilibrium models provides a summary of equilibrium modeling principles. He states the objectives and methods of the market equilibrium approach and reviews the work done up to that point. The objective of this approach is to determine the efficiency of the natural gas industry by the application of neoclassical economic modeling principles. The advantages of the approach are that market equilibrium models are straightforward to design and understand and provide a clear image of how the market should behave if it adhered to the principles applied. Unfortunately, it is also a rather idealized model of the industry which means that model results are often far from realistic. Smeers proposes that the assumption of perfect competition be used only as an ex post tool to see how closely the industry resembles the perfect competition model. For an ex ante analysis he proposes the use of imperfect competition models that compute Cournot and Bertrand equilibria. Finally, he discusses the possibility of using multistage models to include investments, but concludes that the computability of such models is still problematic. In a later article, Gabriel & Smeers (2005) present an extensive overview of various more advanced methods for market equilibrium modeling.

A classic application of this modeling approach and a basis for much of the later work is Golombek et al. (1995), who use a model of the West-European gas market that assumes complete liberalization. Producers are modeled as Cournot profit maximizers on a country level. Consumers are also modeled on a country level, are divided into two types, industry and households, and have linear demand curves. Transport and flexibility services are assumed to be supplied at long-run marginal cost in sufficient quantities. Equilibrium prices and quantities are calculated by applying an optimization technique. The model is then used to study the welfare effects of liberalization under different degrees of arbitrage. A later study by Golombek et al. (1998) uses the same model to suggest that, in a liberalized market, it is profitable for a country to split up its national producer into two companies.

This model was adapted by ECN (Boots et al., 2004) to study the role of trading companies. In their model, producers supply gas to traders on a country border and traders sell to the consumers within a country. They conclude that a successive oligopoly could form, implying double marginalization, and recommend promoting vertical integration to prevent this. Holz et al. (2005) extend this approach by including global supply and more detail with regard to actor types. The Netherlands Bureau for Economic Policy Analysis (CPB) uses a similar model, but with transport operators and storage operators also included (Zwart and Mulder, 2006). It is used to calculate the economically optimal production of the Dutch Groningen field. Perner and Seeliger (2004) use their EUGAS model to make long term predictions (from 2005 to 2034) about European natural gas supply. They describe their approach as follows. "The logic of the model algorithm is that of a perfectly informed central decision maker who optimizes social welfare." Their results show that no gas scarcity will arise and prices will not increase substantially. Gabriel et al. (2005) apply the equilibrium modeling technique to the North-American market, and use it to study the potential extent of market power for different scenarios. Finally, Hartley and Medlock (2005) develop a model for analyzing global gas trade by modeling resources demand and infrastructure for the whole world. It is important to note that all of the models using this approach draw conclusions based on the assumption that equilibrium is reached. The question of whether equilibrium is reached and if so under which circumstances is not dealt with.

There are also some natural gas market models worth discussing which use variations on the market equilibrium technique. Avery et al. (1992), model the gas market from the perspective of one actor. They optimize the conditions of purchase, storage and transmission contracts for natural gas utilities. The optimization algorithm can be interpreted as a decision algorithm for one of the actors in the industry.

Pagliero (2003) uses a game-theoretical approach to study the interaction between shippers when booking capacity for an entry point on the British grid. His analysis shows that specific regulation can be the cause of unexpected actor behavior. This suggests that regulation and the incentives it creates for actor behavior should be included in models to obtain an accurate description of the industry.

Ellis et al. (2000) emphasize the importance of company strategy in determining industry structure. They use a scenario approach to show how company actions such as horizontal, vertical and lateral integration can change the shape of the natural gas industry. This suggests a wider range of actor behavior should be considered than is normally done in such models.

Finally, Hubbard and Weiner (1986) model a contract between a natural gas producer and a pipeline company. They show that when uncertainty about future demand is introduced along with high transaction costs, long-term contracts with take-or-pay and price-linkage provisions arise naturally. In such a situation, there is no market-clearing equilibrium to calculate.

It has been recognized that the market equilibrium approach to natural gas market modeling can be unsatisfactory. The limitations of equilibrium modeling were first discussed by Bunn and Dyner (1996). They argue that many policy issues facing the energy sector cannot be addressed with such an approach, as a number of assumptions must be made about the functioning of the industry which are seldom fulfilled. The main faults listed are the lack of non-linearity and feedback, the lack of behavioral aspects and the lack of dynamics. Gary and Larsen (2000) also emphasize that equilibrium models are not suitable for the analysis of industries that are in the process of liberalization. They go on to present a system dynamics model for electricity generation capacity investment that uses explicit decision algorithms for actors influenced by limited information feedback and show that results differ significantly from equilibrium approaches.

The problems with the market equilibrium approach can be clarified by an example tailored to the natural gas market. Figure 3.1 portrays a simple model of the price mechanism. The arrows one to four show the relations between the supply, demand and price variables that are assumed to hold in a market equilibrium model. Pluses and minuses indicate positive and negative relationships respectively. In addition to being assumed to exist, they are assumed to generate equilibrium rather than fluctuations around equilibrium. This is problematic for several reasons.

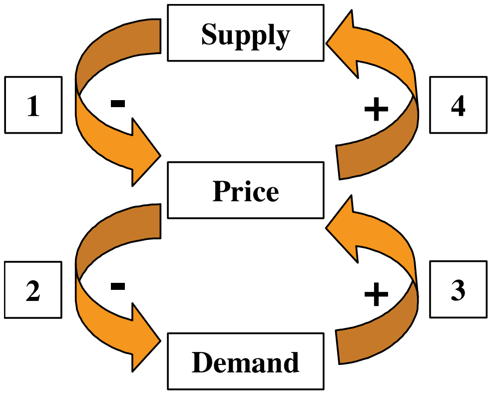


Figure 3.1: the relations between supply, demand and price in an equilibrium model.

Arrows 1 and 3 show the influence of supply and demand on price. In continental gas markets, prices are often linked to oil prices. As a consequence, an increase in supply does not automatically lower prices and an increase in demand does not raise price. Instead, most producer-consumer relationships are guided by long term contracts in which the consumer gains the right of uninterrupted supply and the producer receives a sales guarantee. The commodity price is linked to that of competing fuels and the consumer pays a premium for flexibility in the amount he consumes over a certain period.

Arrow 2 shows the influence of price on demand. The degree to which this relation exists is measured by a consumer's demand elasticity. For many consumers, this elasticity only exists in the long term. It is zero in the short term as consumers either cannot easily decrease their consumption (e.g. industry with methane feedstock and electricity producers) or are not aware of price increases (e.g. households).

Arrow 4 shows the influence of price on supply. This influence is subject to a time lag equal to the time it takes to explore for gas and get it to a market. In addition, an increase in supply will only materialize when there are natural gas fields that become profitable to exploit with a certain price increase. In a developed market, this will only be the case for very small fields as larger fields are profitable to exploit already. Therefore, the effect on supply will be small.

Such methodological problems will be exacerbated in situations where the security of supply is at stake, e.g. when temperature is low and important facilities fail. While it can be argued that useful lessons can still be learned from such models by studying one deviation from equilibrium at a time, applying the results to policy questions is problematic. The general theory of second best (Lipsey and Lancaster, 1956) has shown that the positive effect of a policy in a perfect market says nothing about the effect of a policy in a market with one or more imperfections, which means policy advice should take into account all market imperfections simultaneously.

To avoid the problems listed above, some form of dynamic system modeling is required. Equilibrium then becomes a special case in a more general dynamic framework (Arthur, 2006). Two main branches of dynamic system modeling exist: system dynamics and agent-based modeling. Both have been used to model the natural gas market on a few occasions.

Clark (1985) uses a simulation model to calculate the operating margin that is needed by the national (British) transmission system operator to cover supply shortfalls. The simulation method is used because interacting events are studied rather than a single decision. Bunn and Dyner (1996) introduce a system dynamics model for consumer switching behavior from electricity to natural gas. North (2001) is the first to use an agent-based approach that spans most of the value chain by modeling producer and consumer agents constrained by infrastructure. This bottom-up approach allows him to model aspects of the market not found in other models. These include producers going bankrupt, consumers not being supplied and the failure of infrastructure components. Pelletier (2006) uses an agent-based approach to model planning in gas transmission. The model represents agent behavior in detail, but covers only part of the value chain.

The main difference between system dynamics and agent-based modeling is that they use different building blocks for their models. System dynamics starts with assumptions about the causal relationships between relevant factors, whereas agent-based modeling starts with identifying actors and their behavior. A detailed comparison of the two methods is made by Macy and Willer (2002).

Which method is most appropriate depends on the type of question one needs an answer to. Unfortunately, the choice of model as a function of the question at hand is hardly ever considered in the literature. As the objective of this chapter is to identify the model features necessary for this study, the next section categorizes the features found in existing models and clusters them along three dimensions. This will allow the structure of a model to be expressed as a position in three dimensional modeling space.

3.2 Three dimensional modeling space

3.2.1 Earlier work

The design of a general classification system for natural gas market models has not been attempted before. However, Ventosa et al. (2005) have identified some trends in electricity market modeling. Their main classification is into single firm optimization models, market equilibrium models and simulation models. They define some other model characteristics as well, which can be grouped into:

1. Mathematical aspects: calculation methods (optimization/simulation/equilibrium) and uncertainty (deterministic/probabilistic).

2. Technical aspects: representation of the generating system (low/medium/high accuracy) and the transmission network (single node/linear/non-linear).
3. Economic aspects: degree of competition (monopoly/oligopoly/perfect competition) and market modeling (exogenous price/single firm residual demand/imperfect market equilibrium).
4. Temporal aspects: time scope (days/months/years) and links between periods (intra-period/inter-period).

The identification of these characteristics allows models to be compared from many different perspectives. However, they do not translate easily into an overarching framework by which to classify models. Therefore, they are rearranged somewhat, with some characteristics added and others removed, to form the classification system presented below.

The number of existing gas market models is much smaller than the number of electricity models. (Ventosa et al. review some 36 models versus 15 models reviewed in this chapter.) Therefore, the classification proposed in this section has a broader aim. Its purpose is not only to structure existing work, but also to identify possible future modeling approaches.

The classification attempts to cover all issues relevant to modeling the natural gas market. For clarity, they are grouped into three modeling dimensions. The first deals specifically with the limitations of market equilibrium modeling and is called the market imperfections dimension. It consists of four characteristics: actor motives, actor behavior, price formation, and dynamics. The second and third dimensions deal with more general modeling issues. The second is called the model scope dimension. It deals with the issue of which phenomena to treat endogenously and which ones to treat exogenously. It consists of five characteristics: modeling perspective, inclusion of regulation, value chain length, temporal scope and geographical scope. The third is called the model granularity dimension. It is concerned with the amount of detail that is required in the representation of the endogenous phenomena. It consists of three characteristics: actor detail, temporal detail and technical detail. The characteristics that constitute the dimensions are described in the next three subsections. A potentially important characteristic covered by Ventosa et al. but left out of this classification is the phenomenon of uncertainty, i.e. whether to model deterministically or probabilistically. The classification is limited to deterministic modeling as no probabilistic model exists yet and the introduction of probability is considered too advanced for the scope of this study.

3.2.2 Market imperfections

The "market imperfections" dimension measures the degree to which a model incorporates the natural gas market's deviations from perfect market assumptions. Four characteristics are defined that together determine the position a model occupies on this dimension:

- Actor motives: profit maximization vs. other goals. The simplest way to model motives is to assume that companies aim to maximize profits and consumers aim to maximize utility. However, several alternative assumptions can make the model more realistic. First, the involvement of the state in the natural gas market means that many actors are either controlled by the state, which means they maximize social rather than commercial goals, or are assigned public duties which they have to balance with their own goals. Second, even purely commercial actors can have alternative motives, such as risk aversion, market-share maximization or satisficing instead of optimizing with regard to profit. Third, within the confines of profit maximization, there is a choice between short-term and long-term profit maximization, which affects e.g. investment.
- Actor behavior: substantive vs. procedural rationality. In economics, there are two main approaches to modeling behavior. The first is to select an action based on its outcome, the second is to model the process of action selection. In the first case, it is often assumed that a company will successfully choose that course of action which optimizes the outcome of its behavior with regard to its motives. This assumption is called substantive rationality. In computer models, this assumption leads to either a single-firm optimization problem or a multi-firm market equilibrium problem. There are, however, many examples of circumstances where this is not an adequate description of a company's behavior. When a company's environment reaches a certain degree of complexity, the assumption that a company always succeeds in optimizing its actions leads to errors. Arguably the most important of these environmental complexities is the lack of information about the actions of other companies and about future demand and supply conditions. In the second case, a procedure for selecting an action is chosen that aims to optimize behavior but does not necessarily succeed. This is called procedural rationality. In computer models, such rationality is represented by rule-based decision algorithms. A choice between the two should depend on whether an optimum is expected or behavior is expected that will prevent the optimum from being reached. In the former case, the most important thing is where that optimum lies, which can best be calculated with an optimization model. In the latter case, such behavior should be simulated. An alternative, mixed approach is the use of partial optimizations in a larger simulation framework. This combines the best of both worlds by allowing optimizations where applicable and alternative decision algorithms where necessary. At present, few models extend company behavior beyond substantive rationality. When they do, they mostly focus on a single form of strategic behavior which is expected to generate substantially different results.
- Price formation: gas-to-gas competition vs. oil price linkage. This feature is closely related to contracting. In long term agreements prices are often fixed at rates derived from other commodities, mostly oil products. In the short term, prices are formed on the market in an impersonal exchange. In

practice, most companies have portfolios of both long term and short term contracts which are expected to move further toward the short term in the future. By far the most models include gas prices as an endogenous variable as a function of quantities produced. Whether this is an acceptable simplification depends on the study, but generally it causes both actors' price responsiveness and their influence on price to be overrated. A mixed approach is therefore used by some. The CPB uses a combination of market pricing and LNG price links (Zwart and Mulder, 2006), whereas Ellis et al. (2000) use an exogenous price combined with some short term market pricing. More generally, the difference in price formation can be traced to the way governance structures are incorporated in a model. On a market, prices are the result of a supply and demand equilibration process, whereas in bilateral contracts, some other procedure must be used to reach a price agreement.

- Dynamics: static equilibrium vs. dynamic path. In a perfect market, a unique equilibrium exists for every conceivable market situation. In simulations that cover a longer period of time, market outcomes are represented as series of equilibria. In reality, the market is never in equilibrium, but traces a dynamic path through state-space as actors act and react to changing circumstances and to each other's actions. Although no model is truly continuous, the more it incorporates these out-of-equilibrium dynamics the better it is able to represent and explain developments in the natural gas market. In general, it can be said dynamics are important when there are doubts about the convergence to and/or the stability of an equilibrium.

3.2.3 Model scope

This dimension determines the boundaries between the modeled system and its environment.

- Perspective: single firm vs. industry. This feature is concerned with the perspective from which the model is built. Single firm models are concerned with the question of how a firm can best react to its environment. Industry models instead deal with the performance of an entire industry. The choice for one of these models follows directly from the intended user of the model. If the user has little or no influence on developments outside his own company, single firm models are more appropriate. Most of the models reviewed are industry models, whose goal is to measure the efficiency of the entire industry.
- Regulation: implicit vs. explicit: Rules set forth by the European Union, national governments and regulatory authorities function as boundary conditions for the industry to operate within. However, regulation has received little attention in natural gas market models. It is often assumed that the effects of regulation are limited to guarding the competitive market, whereas in reality, regulation plays a crucial role in the functioning of the market. Examples of this are third party access and exemptions, public

investment regulation and the scrutinization of traditional contract provisions. In addition, the assumption of regulation remaining constant disregards the dynamics between industry and regulator. On the one hand, events in natural gas supply affect political opinion and, with a time lag, regulation. On the other hand, dynamic regulation is a large source of uncertainty for the industry which has to consider several options and scenarios for regulations when determining its strategy.

- Time length: short term vs. long term. Usually, the distinction between the short and long term is made by saying that in the long term all fixed inputs become variable. For the natural gas industry, this means in the long term investments are included with a realization time of several years and an economic lifetime of 10-50 years. The more theoretical models that are used to demonstrate a principle often do not explicitly mention time at all. They simply derive a single result from their model independent of time. If such models include the long term, they are two-stage models with an investment stage preceding a supply stage. Simulation models as well as models that focus on predictions for a specific time and place use an explicit timescale ranging from one to thirty years.
- Value chain length: holistic vs. partial. The value chain ranges all the way from exploration to consumption and in principle only models that comprise the whole chain are considered in this review. However, as mentioned earlier, some models with a more limited scope can provide useful examples of alternative modeling techniques. In some cases, a model reaches beyond the natural gas value chain and into the electricity market. At a minimum, this requires treating some natural gas consumers as electricity producers and adding electricity consumers to the model.
- Market scope: small vs. large. A “market” is a notional point where supply and demand meet. An assumption underlying all models is that the geographical area modeled can be considered as a single market. In the case of a large area like Western Europe, this requires some assumptions about the action radius of actors in the industry, as well as the availability of physical connections between countries. In the case of a smaller area, e.g. a single country, it requires some assumptions about the feasibility of modeling neighboring regions exogenously.

3.2.4 Model granularity

This dimension measures the amount of detail that is included in the modeled system.

- Actor types: aggregation vs. differentiation. In its simplest form, a market can be represented by a single producer and a single consumer which determine supply and demand respectively. However, things can be made both more complex and more realistic by differentiating actors into different types, such as producers, traders, transmission operators and storage operators, and into different actors from the same type. In recent years, the natural gas industry has seen much restructuring in the form of unbundling, vertical (dis-)

integration, mergers and acquisitions. To account for these changes, more detail in the amount and type of actors is necessary. The choice to include extra actors should be made on the basis of the expectation that they will add a strategic element to the model. The inclusion of different actors varies widely between models reviewed, covering the whole spectrum.

- Time step: none vs. short vs. long. Three types of model can be distinguished for this feature. There are models that calculate a single optimum and therefore do not use time steps at all, models that calculate sequential optima over several longer time periods and models that simulate developments over shorter time steps. The smallest time step in a model should be chosen on the basis of two considerations. First, whether the focus of the model is operational or strategic. Second, whether important non-linearities are expected to surface when the amount of detail is increased. For instance, the modeling of investment rates would imply a large time step, unless the decision to invest hinges on peak day demand, which obviously needs a smaller time step to be included. In the models reviewed, the time step varies from one day to five years.
- Technical detail: low vs. high. Both in the sense of geological features and of physical infrastructure, technical characteristics place important restrictions on actor behavior. The three main types of asset found in the natural gas industry are producing fields, storage facilities and transport networks. Many models use countries as their basic building blocks, treating them as a single producer and/or consumer region with a certain international connection capacity. This seems acceptable for questions dealing with cross-border European transport and consumption, but can be misleading when assumptions are made about, for example, the distribution of gas flows over entry points of the network. In general, the required amount of detail is highly dependent on the use of the model.

In the next section, the models discussed in Section 3.1 are analyzed with regard to the dimensions described in this section.

3.3 Positioning existing models in 3D modeling space

The three dimensions described in the previous section can be used to create a three dimensional modeling space in which gas market models can be positioned on the basis of their main characteristics. Figure 3.2 shows the position of existing gas market models in this modeling space.

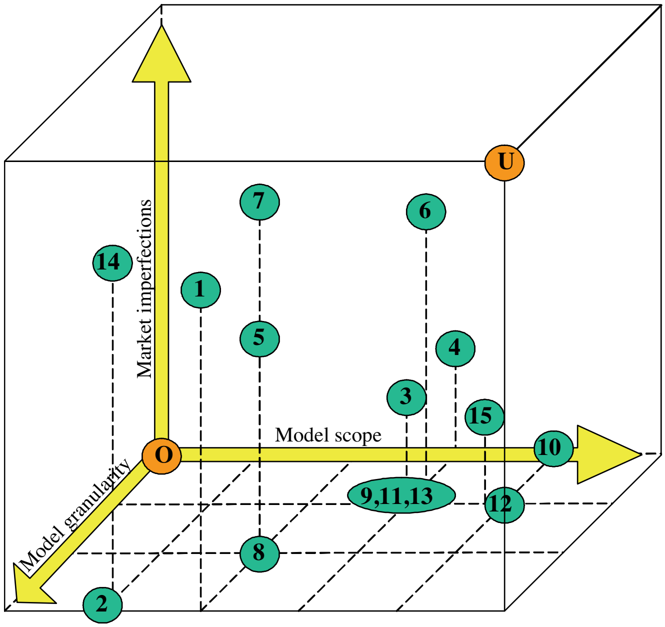


Figure 3.2: Existing models plotted in three dimensional modeling space.

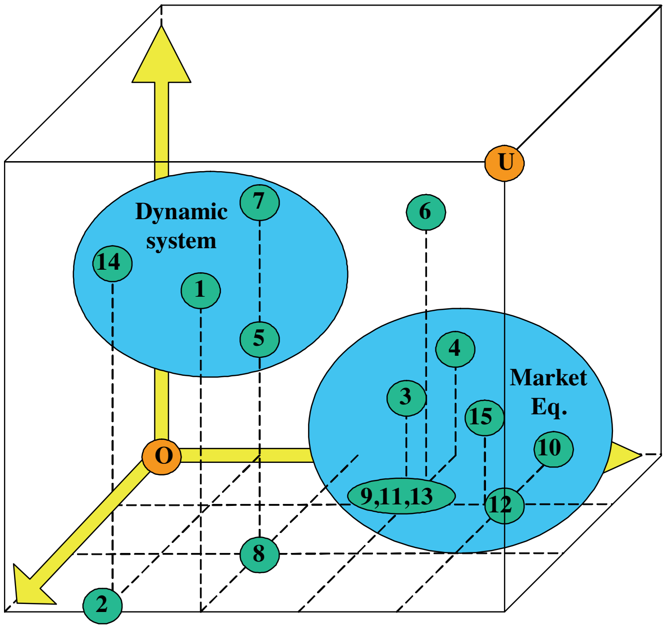


Figure 3.3: Existing models grouped into two modeling methods: dynamic system modeling and market equilibrium modeling.

The O in the origin of the modeling cube stands for an imaginary model that scores zero on all dimensions. This model is in effect the textbook market equilibrium model without adjustments for the special characteristics of the natural gas industry. The U in the opposite corner of the cube stands for the utopian, comprehensive model which takes into account all relevant aspects of the market as identified in the previous section. This position is desirable but practically unattainable. The numbers 1 to 15 stand for the models reviewed in the previous section. The scores per model with regard to each characteristic are shown in Table 3.1.

Section 3.1 contrasted two modeling approaches; market equilibrium modeling and dynamic system modeling. The modeling cube can also be used to identify the characteristics of both approaches. Figure 3.3 shows the location of dynamic system models and market equilibrium models in modeling space. Although the figure is highly stylized, it shows a clear trend. Dynamic system models generally score high on granularity and market imperfections but low on market scope. Market equilibrium models, on the other hand, generally score high on market scope, but low on both granularity and market imperfections.

The relevance of this classification rests on the assumption that two models with different positions in modeling space will yield different results, when the situations modeled are identical. In other words, the relevance of this study rests on the hypothesis that the positioning of a model in the modeling space created above will in most cases significantly influence model results and policy decisions made on the basis of these results, and that an inverse decision-based approach to model design is therefore required to understand a priori which position in modeling space is fit for purpose. This hypothesis will be tested in the remainder of this study.

Table 3.1: Models scored on the basis of the three dimensional categorization developed above.

Model			Market imperfections				Model scope					Model granularity		
Number	Author(s)	Year	Actor behavior	Out-of-eq. Dynamics	Actor motives	Price formation	Perspective	Time length	Value chain length	Market scope	Regulation	Actor types	Time step	Technical detail
1	Clark	1985	proc.	y	public goals	none	actor	short	partial	U.K.	yes	transport op.	1-day	high
2	Avery et al.	1992	subst.	n	cost min.	exogenous	actor	long	partial	U.S.	no	utility	none	high
3	Hubbard & Weiner	1986	subst.	n	LT profit max.	function of contract & regulation	industry	long	partial	U.S.	yes	producer, pipeline co.	none	low
4	Golombek et al.	1995, 1998	subst.	n	ST profit max.	g-to-g comp.	industry	short	whole	Europe	no	producer, consumer	none	low
5	Bunn & Dyner	1996	proc.	y	LT cost min.	exogenous	actor	long	partial + electricity	Colombia	no	consumer	1-year	low
6	Ellis et al.	2000	proc.	n	strategic	mixed approach	industry	long	whole	Europe	no	varies per scenario	large	low
7	North	2001	proc.	y	LT profit max.	g-to-g comp.	industry	short	whole + electricity	general market	no	producer, consumer	small	high
8	Pagliero	2003	subst.	n	ST profit max.	none	industry	short	partial	U.K.	yes	shipper	2-stage game	high
9	Boots et al.	2004	subst.	n	ST profit max.	g-to-g comp.	industry	short	whole	Europe	no	producer, trader, consumer	2-stage game	low
10	Perner & Seeliger	2004	subst.	n	social welfare opt.	none	industry	long	whole	Europe	no	central decision maker	5-year	low
11	Gabriel et al.	2005	subst.	n	ST profit max.	g-to-g comp.	industry	short	whole	U.S.	no	prod., cons., marketer, storage op.	none	low
12	Hartley & Medlock	2005	subst.	n	LT profit max.	g-to-g comp.	industry	long	whole	World	no	producer, consumer	2-year	high
13	Holz et al.	2005	subst.	n	ST profit max.	g-to-g comp.	industry	short	whole	Europe	no	producer, trader, consumer	2-stage game	low
14	Pelletier	2006	proc.	y	optimize cost vs. risk	exogenous	industry	short	partial	general market	no	producer, trader, transport op.	none	low
15	Zwart & Mulder	2006	subst.	n	LT profit max.	mixed approach	industry	long	whole	Europe	no	prod., cons., transport op, storage op	5-year	low

3.4 A natural gas market model fit for purpose

Returning to the aim of this chapter, the classification system can now be used to explicitly state the design requirements of a model for studying the tradeoff between affordability and supply security. This is done by considering for each dimension both the minimal requirements of the model and the optimal model structure. Actual models will mostly be somewhere in between these two extremes, as there is a tradeoff to be made between the optimality of model structure and the feasibility of its development. As the following remarks are based solely on theoretical considerations, they have the status of hypotheses to be tested in model development.

Before turning to the specific dimensions, a general modeling methodology must be chosen. As discussed in Section 3.1, market equilibrium models cannot represent the market imperfections identified above, so some form of dynamic system modeling is required. Given the importance of actor behavior, and given the fact that most causal relations are not known a priori, an agent-based model is more appropriate in this case than a system dynamics model and will therefore be adopted as the general methodology for this study.

The choice for agent based modeling has large consequences for the market imperfections dimension. First, out-of-equilibrium dynamics are a natural component of agent based models. Second, actor behavior must be specified, which implies the incorporation of procedural rationality. Therefore, these two market imperfections are more or less unavoidable. Furthermore, the inclusion of oil price linkage is necessary to provide the model with a realistic price evolution. When these minimal requirements are incorporated in a model, it can be made optimal by fine-tuning the agents' motives and behavior. Short term profit maximization on the basis of simple decision algorithms provides a good starting point, after which the model can be made more realistic by including alternative motives and more sophisticated behavior.

When determining the model's scope, two considerations oppose each other. On the one hand, the scope should be kept to a minimum to keep the model tractable and understandable. On the other hand, affordability and supply security are features of the whole value chain, which suggests a large scope is required. Therefore, a multi-firm perspective that covers the whole value chain is a minimal requirement. To limit complexity, regulation will initially remain exogenous (but explicit) and the typical market scope will be that of a single country, with international flows modeled exogenously. The long term will be included where necessary with an optional investment module. Eventually, optimality can be achieved by endogenizing regulation and increasing market scope.

The third dimension, model granularity, is important for the reason that aggregation of actors, time and technical assets may hide non-linearities in the distribution of the aggregated variables. For each of the three aspects, a criterion must be chosen to determine the required granularity of the model. In the case of actors, the criterion is that each type of autonomous decision maker must be represented separately, which means that decision makers of identical type, e.g. small consumers, are aggregated into a single decision maker. In the case of time, a granularity of one day is chosen under the assumption that within day fluctuations are evened out by the transport network's linepack. In the case of technical assets, each asset will be represented individually (with the possible exception of some very small gas fields), but initially in a simplified way (e.g. a network without linepack). If necessary, more detail can be added for specific case studies, thereby moving closer to the optimum.

In the next chapter, a detailed description is given of a modeling framework adhering to the principles set out in this chapter. This framework should be able to generate models which can occupy any point in modeling space. In other words, the whole modeling cube is covered by this framework. The study will then proceed by using the framework to develop a series of initially simple, but increasingly complex models, until a model is built which satisfies the minimal requirements outlined above. This model will form the basis of some case studies, in which some additions to the model are made. This will move the model closer to the optimum. On the basis of these studies, the accuracy of the choices concerning modeling methodology made above can be ascertained. Figure 3.4 shows the initial simple model, denoted by E, the move towards a model satisfying the minimal requirements, denoted by E', and the move towards the optimal or utopian model, still denoted by U.

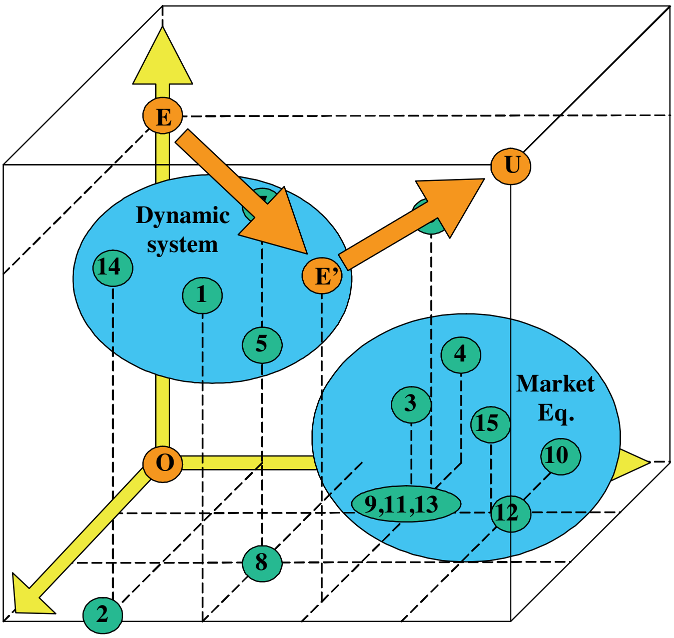


Figure 3.4: The starting point for modeling (E), the minimal requirements for a model (E') and the chosen path towards optimality.

4. The ENETSIM framework

4.1 Model structure

As explained in the previous chapter, the methodology underlying the current generation of natural gas market models has a number of limitations. In a nutshell, these limitations amount to the inability to account for a number of market imperfections inherent to the natural gas market. Therefore, a new methodology is required which can include those market imperfections. One of the aims of this study is to develop such a methodology, and the results from this development process are described here. This chapter is limited to a general description of the framework. In the next chapter, some relatively simple models will be constructed to verify the methodology. In Chapters 6 and 7, the methodology is applied to an analysis of the Dutch gas market.

ENETSIM (Energy NETwork SIMulator) provides a modeling environment which can be used to build natural gas market models. ENETSIM has been developed specifically for the purpose of studying security of supply and affordability simultaneously, and choices made about the structure and dynamics of the model reflect this. The methodology is a form of Agent-based Computational Economics (ACE). ACE is defined in Tesfatsion (2006) as "the computational study of economic processes modeled as dynamic systems of interacting agents". The ACE approach proceeds by identifying agents, their individual behavior, and their local interactions with other agents. From their behavior and their interactions, global system behavior emerges. In contrast to most of the agent-based literature, the ENETSIM methodology also explicitly defines and discusses the boundary between the dynamic system and its environment and the interactions between system and environment. In this respect, it bears resemblance to the system dynamics modeling school and systems thinking in general.

ENETSIM provides a 'library' of natural gas market agents. ACE defines agents as "bundles of data and behavioral methods representing an entity constituting part of a computationally constructed world" (Tesfatsion, 2006). The library consists of five actor agents and three institutional agents. The actor agents together span the entire natural gas value chain from exploration to consumption and are called User, Trader, Network Operator, Resource Operator and Storage Operator. Actor agents can interact in three ways: through Market agents, through Contract agents or through Integration agents (i.e., integration within a single company). These interactions are represented by institutional agents. Agents are described in detail in Section 4.5.

Models are implemented in the computer program Simulink, which is an extension of Matlab designed specifically for dynamic system simulation. A natural gas market model created with ENETSIM is a quantitative, dynamic system. The structure of each model is determined by the number of actor agents of each type included in it and the way in which these actor agents interact through markets, contracts and integration. This means the structure of a model can be characterized by the shape of its agent network. When the number of actor agents of each type and the type of institutional agents through which they interact are fixed, the model is made operational by specifying the behavior of each agent and by adding data, which consist of the initial values of state variables and of model parameter values. Since the agent network remains constant throughout the simulation, the time dependent system state at each time step is determined by the values of all state variables. There are three types of state variable: contract states, physical states and financial states. The variables' initial values determine the system's initial state. The system then evolves over time in discrete, single day time steps. At each time step, the model generates output at the level of individual agents. In addition, the model generates system level output, which consists of values for the indicators of affordability and supply security.

This means that, in a nutshell, the model can be described as a function:

$$(A, SoS) = f(N, B, D) \tag{4.1}$$

With:

A	=	Affordability, i.e. prices paid by consumers
SoS	=	Security of supply, i.e. the (probability of) fulfillment of security conditions
N	=	The shape of the agent network
B	=	The behavior specified for each of the agents
D	=	The model dataset

4.2 Model dynamics

The system's short term dynamics consist of flows of information, gas and money. The transition from one day to the next occurs in four steps. First, agents send out and receive information about demand, physical states and contractual states. Second, they make decisions on the basis of both received information and the structure of their decision algorithms. All agents make their decisions simultaneously. Third, according to their decisions, they send out and receive gas. Fourth, transactions are completed by sending and receiving money. This process is shown in Figure 4.1.

The system's long term dynamics consist of changes in physical and contractual states. Basically, states that are constant in the short term become variable in the long term. These long term changes are governed by an additional set of agent decision algorithms. Contract states change as an outcome of (re-)negotiation between contract partners. Physical states change as a result of investment decisions made by actor agents. Network operators can increase the capacity of their networks, storage operators can build additional storage facilities and resource operators can explore the subsurface to discover new gas reservoirs.

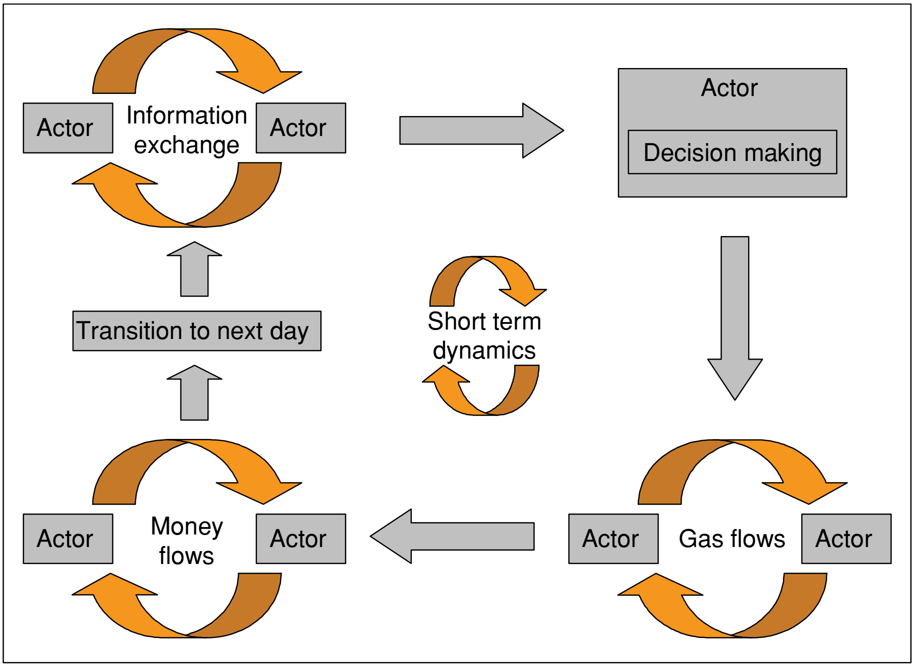


Figure 4.1: The system's short term dynamics.

4.3 Model boundary

The location of the boundary between the system and its environment determines the model's scope. In other words, it determines which phenomena are treated as endogenous variables and which are either treated as exogenous parameters or are not included in the model at all. The four most important exogenous factors included in the ENETSIM framework are:

1. *The oil market.* Oil price is treated as an exogenous parameter, although it can be programmed to change value during the simulation.
2. *The electricity market.* Electricity producers can be included as user agents, with decision algorithms tailored to the specific circumstances of electricity production.
3. *Other natural gas markets.* Although in principle ENETSIM can be used to model the global gas market, a model usually represents a national or regional market. Therefore, other natural gas markets are connected to the modeled market via import and export. Import is treated similarly to production, whereas export is treated similarly to consumption.
4. *The regulatory environment.* It could be said that the regulator is the intended user of the model rather than a part of it. Regulation is included as a set of constraints applied to the model. These constraints are mainly of four types: the forced unbundling of actor agents, price regulation, forced third party

access to infrastructure and constraints applied to the behavior of specific agents. In a later stage of development, regulation could be endogenized by, for example, including the regulatory authority as a separate actor agent.

The boundary between system and environment is summarized in Figure 4.2.

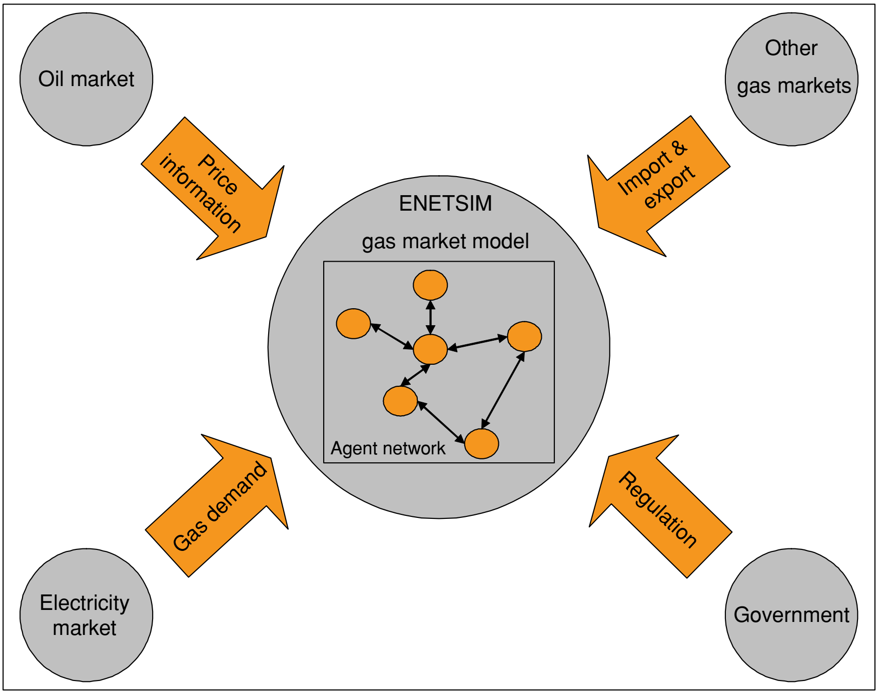


Figure 4.2: The boundary between the system and its environment.

A possibly important exogenous factor which is currently not included in the model is the market for CO_2-emissions. First of all, the price of emission rights influences the attractiveness of natural gas vis-à-vis other fuels. Second, the emerging technology of CO_2-storage could lead to competition for empty natural gas reservoirs between two purposes: storing natural gas and storing CO_2.

4.4 Model output

Two types of model output can be distinguished. First, there is the agent-level output generated by each agent. Second, there is the system-level output which can be obtained by post-processing the agent-level output. These two levels of output correspond to the two levels incorporated in the conceptual model constructed in Section 1.3.

The basic output of each actor agent is its money stock, which is equal to the integral of its net profit. This is the quantitative indicator used to determine the degree to which the individual actor agents succeed in achieving their optimization objective (as indicated in Figure 1.6). In addition, each actor agent generates some output specific to its type. For example, a user agent's output also includes its demand for natural gas, its consumption of natural gas, and its choice of supplier. These outputs are described for each agent in Section 4.5.

The agent-level output of institutional agents differs per type. Market agents generate the price and net quantity of natural gas traded on the market. Contract agents generate the price of the product delivered under the contract, and in some cases upper and lower bounds to the quantity. Integration agents don't generate output of their own. They are used to create compound actor agents, and in so doing influence the output generated by these new actor agents.

As discussed in previous chapters, the ultimate goal of the methodology is to quantify affordability and supply security. Quantitative indicators of these concepts are therefore the main system-level outputs of a model. These indicators have to be inferred from the agent-level output generated by the agents.

Since price has been chosen as the indicator of affordability, it is to be decided which of the prices generated should be used for this purpose. Often used indicators are wholesale prices (both spot and long term contract) and end-user prices. Depending on the question at hand, a combination of these prices can be used to determine affordability. In general, however, end-user prices are the most suitable indicator, as they ultimately determine affordability for end-users. Furthermore, as the simulations performed have a certain time length, time series of prices are generated rather than a single price. These time series can be processed further to generate an average price as well as its volatility. In this study, volatility is defined as the standard deviation of the daily change in price.

The definition of supply security provided in Section 2.6 comprises three conditions. Supply should equal demand (Eq. 2.1), physical flows should be in line with economic outcomes (Eq. 2.2), and price should not exceed a certain threshold (Eq. 2.3). The satisfaction of all three conditions can be inferred from the agents' outputs. Three outputs from the user agent can be used to infer 2.1 and 2.2: a user's demand, the supply it is legally entitled to and the supply it actually receives. If its demand is larger than the supply it is entitled to, the quantity condition is violated. If the supply it is entitled to is larger than the supply received, the physical condition is violated. If a network operator agent is included in the model, the physical condition can be inferred directly from the system integrity variable associated with each physical network (see § 4.5.5), which determines whether users can withdraw the amount of gas they are entitled to from the network.

Verifying the price condition requires knowledge of the price and of the maximum acceptable price. The price is model output, as explained above. The maximum acceptable price is the most difficult to establish, as it depends on a value judgment about what is acceptable. This is left to the user of the model to decide.

With regard to supply security, model output is binary: either supply is secure, or it is not. To calculate the probability of secure supply, a series of simulations is required in which the relevant parameters are varied. From the results obtained, probabilities can be calculated or threshold values can be established.

4.5 ENETSIM agents

As explained above, an agent network consists of a maximum of five types of actor agent. These are called User, Trader, Network Operator, Resource Operator and Storage Operator. Together, they span the entire natural gas value chain from exploration to consumption. The choice for this combination of agents was motivated by the following general considerations:

- As a starting point, an actor agent is roughly equivalent to one step in the value chain.
- Together, the actor agents should be able to represent the whole value chain from exploration to consumption;
- For simplicity's sake, if consecutive steps in the value chain are (nearly) always combined within a single company, they are modeled as a single agent;
- If not, they are modeled as separate agents.

With these principles in mind, a useful set of actor agents can be derived from the value chain constructed in Section 2.1. First of all, the whole upstream section of the value chain (exploration, production and processing) is modeled as a single agent. This is in line with empirical observations that these activities are invariably performed within a single firm. Second, different parts of the value chain which are similar can be represented more transparently by using one type of agent twice, than by using two different types of agent. Therefore, transport and distribution are represented by a single agent type.

Third, different technologies used for a single step in the value chain can be used by a single agent. Therefore, LNG liquefaction, transport, storage and regasification do not have to be represented by separate agents. They can be incorporated by the transport and storage agents, which can switch between technologies by liquefying and/or regasifying natural gas where necessary. Finally, there are firms which do not engage in any of the activities comprising the value chain. Their activity is limited to the purchase and sale of contracts. To represent these firms, an additional actor agent is introduced: the trader. From these four choices, the set of five actor agents follows.

These actor agents can interact in three ways: through market agents, through contract agents and through integration within a single organization. These three types of interaction are grouped under the heading of 'institutional agents'. The institutional agents were chosen on the basis of the theory of transaction cost economics (TCE). For a general overview, see Williamson (1975). TCE's chief concern is vertical integration, also called the make-or-buy decision. In the appendix of a more recent paper, Williamson (2007) provides a contractual schema that relates the choice of actors for a certain governance structure to the characteristics of the transaction. The three governance structures are markets, contracts and integration. As the purpose of the institutional agents in ENETSIM is to model the relation between consecutive steps in the value chain, the three governance structures identified by TCE are a useful starting point. The choice for a TCE perspective coincides with an increased recognition of its importance in the gas industry, as expressed in Van Der Linde (2006).

In this section, a description of each type of actor agent is provided which contains its decision algorithms and their structures, its possible interactions with other agents, and the flows of information, gas and money that affect it (§ 4.5.1 - § 4.5.5). Next, each type of institutional agent is described with regard to the way it governs the interactions between actor agents (§ 4.5.6 - § 4.5.8).

All the actor agents described here have a general structure in common. This structure consists of three parts. First, an agent is supplied with an amount of information about its environment. Second, it processes this information in a number of decision algorithms, the form of which is specific to each agent. Third, the outcomes of the decision making processes are the agent's actions and this output is sent to other agents Institutional agents have a similar structure, but their inputs consist of the actions of actor agents, their internal processes are the interactions between actor agents, and their outputs are the results of these interactions (see Figure 4.3).

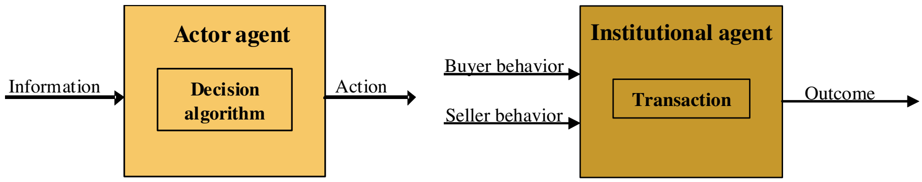


Figure 4.3: The general structure of an actor agent (left), and of an institutional agent (right): input, internal processes and output.

Agents are subsystems of the Simulink model, and are themselves subdivided into a number of subsystems. Each actor agent consists of at least two subsystems: a subsystem containing its main activity, e.g. production or transport, and a financial subsystem. In addition to these, optional subsystems govern an agent's behavior with regard to institutional agents, i.e. contracting and market trading.

With regard to units, it should be noted that most variables are quantified in the form of a monetary unit, a time unit and/or a quantity unit. For simplicity's sake,

throughout the model description the Euro will be used as the monetary unit and the cubic meter as the quantity unit, though this is by no means necessary. Alternative monetary units such as the dollar and the pound, as well as alternative quantity units such as the therm or the kWh, can be substituted without changing model fundamentals.
The time unit used is the day. This unit cannot be changed easily, as the structure of many decision algorithms is based on the assumption that decisions are made on a daily basis.

4.5.1 Users

A user is characterized by two internal processes: the generation of demand for gas and the closing of supply contracts (see Figure 4.4).

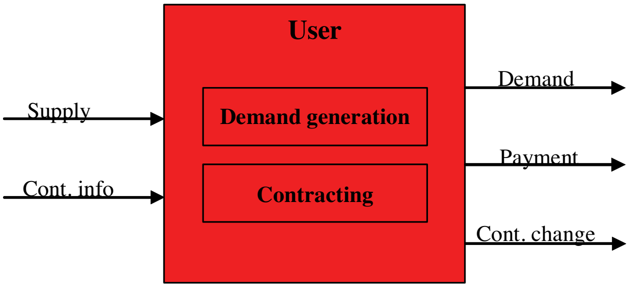


Figure 4.4: The user agent's inputs, internal processes and outputs.

Gas received by a user is removed from the system, and is assumed to be consumed or exported. Its demand is determined on the basis of a demand function modified by price information at the user's disposal. The demand function has the following structure:

$$D(t) = A + B \cdot \sin(t) + C \cdot rand(t) + S_{dp} \cdot (P_0 - P_{t-1}) \qquad (4.2)$$

With:

D	=	User demand in mcm/day
A	=	Average demand in mcm/day
B	=	The seasonality of demand, ranging from 0 to A in mcm/day
C	=	The relative weight of the random component in demand
rand	=	A normally distributed random number with a mean value of 0
S_{dp}	=	A user's sensitivity to price changes in mcm/€
$P_0 - P_{t-1}$	=	The difference between the initial (reference) price and the previous period price in €

It should be noted that modeling seasonality as a sine curve implies that a gas year starts in October instead of January. There are two advantages of using the sine curve.

First, it means that a model run does not start at a peak day but gradually works up to it and second, it is in accord with common industry practice to use October as a starting point.

The demand that is actually sent to the trader that supplies the user is determined by the following function:

$$D_{U \to T}(t) = Min(D(t), C(t), D_{\max - p}(t)) \tag{4.3}$$

With:

D	=	The demand calculated according to (4.2) in mcm/day
C	=	The maximum demand allowed by the user's supply contract in mcm/day
D_{max-p}	=	The maximum demand physically feasible given the user's network connection in mcm/day

A user is linked by contract to one or more traders. As a user agent is often an aggregation of many real-life users with individual supply contracts, a user agent will normally be connected to more than one trader. In addition, a user agent is physically linked to one or more networks. It is, however, highly uncommon for a user to be physically connected to multiple networks.

Each day, a user receives information about prices and contracts. It determines its demand according to Equations 4.2 and 4.3, and sends this demand to the traders supplying him. The user then receives a flow of gas from the network operator, which in most cases will be equal to its demand. If a user's demand is not met entirely, it incurs damage costs. These costs represent the fact that a user cannot perform some of its activities that depend on gas that day.

A user has an initial stock of money. Each day, its money stock increases with a constant income from outside of the system. It decreases with a constant payment for the maximum allowed demand in its supply contract (a capacity fee), a variable payment for the amount of gas it consumes that day (a commodity fee), and possibly damage costs.

$$M_U(t) = M_U(t-1) + I - \left(D_{\max - c} \cdot P_{ut - cap}\right) - \left(Q_{ut} \cdot P_{ut - com}\right) - C_d \tag{4.4}$$

With:

M_U	=	User money stock in €
I	=	Income in €/day
D_{max-c}	=	The maximum consumption allowed by the contract in mcm/day
P_{ut-cap}	=	The user-trader contract capacity price in €/mcm
Q_{ut}	=	Quantity bought from traders in mcm/day
P_{ut-com}	=	The user-trader contract commodity price in €/mcm
C_d	=	Damage costs in €/day

In the long term, a user can change its supply contract in two ways. First of all, it can change the magnitude of its supply contracts, as measured by the aggregate of the maximum daily consumptions D_{max-c} specified in each contract. Maximum daily consumption D_{max-c} is chosen as a function of past demand. Daily demand (D rather than $D_{U=>T}$) is stored in memory and a decision algorithm determines the desired D_{max-c} as a function of its memory. For example, "D_{max-c} equals last year's peak demand". The desired D_{max-c} is sent to the Contract agent (see § 4.5.7) to be processed. Second, a user can change the distribution of its supply contracts by switching between suppliers. The amount of switching that occurs is determined by the price differential between competing offers made by suppliers and a user's natural propensity to switch. This propensity is included to represent the fact that, in real life, switching is also determined by factors not explicitly included in the model, such as supplier reputation, marketing efforts and user inertia. For a user with two suppliers, this amounts to the following:

$$F_{T_1}(t) = F_{T_1}(t-1) + \left(\left(P_{T_2} / P_{T_1}\right) - 1\right) \cdot S_U \tag{4.5}$$

With:

F_{Tx}	=	The fraction of a user's total demand which is supplied by Trader x
P_{Tx}	=	The price of the product sold by Trader x in €
S_U	=	The user's propensity to switch supplier

In case of more than two suppliers, the amount of switching between each supplier pair is calculated individually. The sum of all switches determines the resulting fractions.

4.5.2 Traders

A trader is characterized by three internal processes: its selection of gas sources, its trading strategy on the spot market and its closing of supply, production, storage and transport contracts (see Figure 4.5). It should be noted that a trader with supply contracts of a non-zero value is often called a "supplier" and a trader with transport contracts of a non-zero value is often called a "shipper". These functions are both incorporated into the trader agent, as no company acts as shipper or supplier without also acting as a trader.

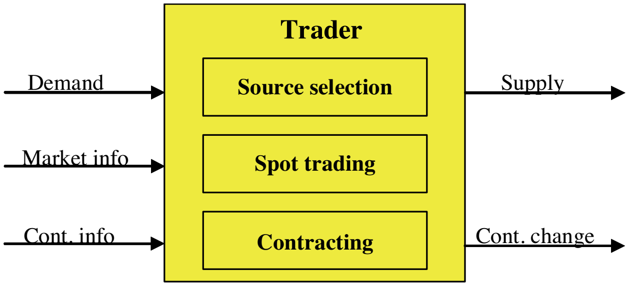


Figure 4.5: The trader agent's inputs, internal processes and outputs.

A trader has two main sources of information, the amount of gas demanded by users and the amount of gas available to him from resource operators, storage operators and the spot market. The trader uses a decision algorithm to match demand and supply. This algorithm takes the form of a "preference scheme". A preference scheme represents a trader's relative preference for available sources of gas by ranking those sources. A trader's preferences are determined by three factors: its contractual constraints, its storage strategy and its assumed goal of cost minimization. The standard preference scheme for a trader that has access to gas from a long term contract, gas from the spot market and gas from a storage and has a storage strategy of saving stored gas as a 'source of last resort' looks like this:

$$RO_{\min} > Spot_{low} > RO_{\max} > Spot_{high} > Storage \qquad (4.6)$$

With:

RO_{min} = The minimum quantity a trader is contractually bound to purchase from a resource operator

$Spot_{low}$ = Spot gas at a price below contract price

RO_{max} = The maximum quantity a trader is contractually allowed to purchase from a resource operator

$Spot_{high}$ = Spot gas at a price above contract price

Storage = Gas stored in a storage facility

A trader matches demand and supply by attempting to purchase an amount of gas from its preferred source equal to total demand. If total demand is higher than the maximum amount available from the preferred source, the remaining demand is purchased from the second-best source and so on, until all demand has been met or until the trader runs out of sources. Traders' behavior on the spot market is described in the section on spot market agents (§ 4.5.8).

A trader decides how to price the gas it sells to users on the basis of its costs and its desired profit rate. The actual price is determined by multiplying the costs made with a markup factor. Commodity costs are equal to the purchasing price, and capacity costs are equal to the price of storage and transport. The markup factor can be input, but it can also be the result of a profit maximizing strategy used by the trader. In a competitive market, for example, traders' markup factors are equal to the minimum profit rate required to stay in business. The markup pricing algorithm is used for several agents and was chosen because of its prevalence in real-world markets. For a comprehensive overview of the empirical support, see Lee (1998).

A trader has an initial stock of money. Each day, its money stock increases with the money received from users and from sales on the spot market. The price of gas supplied to users is decided by the trader on the basis of a markup of the price paid to resource operators. The price of spot gas is determined by a market clearing process (see § 4.5.8). Its stock decreases with the payments made to resource operators, storage operators and network operators for their services, payments made to other traders through the spot market, and a trader's fixed costs.

$$M_T(t) = M_T(t-1) + \left(Q_{ut} \cdot P_{ut-com}\right) + \left(Q_s \cdot P\right)_s - \left(Q_{rt} \cdot P_{rt-com}\right) - \left(Q_{sb} \cdot P_{sb}\right) - \left(Q_{tc} \cdot P_{tc}\right) - C_F \quad (4.7)$$

With:

M_T	=	Trader money stock in €
Q_{ut}	=	Quantity sold to users in mcm/day
$P_{ut\text{-}com}$	=	The user-trader contract commodity price in €/mcm
Q_s	=	Quantity sold on the spot market (negative for quantity bought) in mcm/day
P_s	=	The spot price of gas in €/mcm
Q_{rt}	=	Quantity bought from resource operator in mcm/day
$P_{tr\text{-}com}$	=	The trader-resource operator contract commodity price in €/mcm
Q_{sb}	=	The number of storage bundles contracted
P_{sb}	=	Price of storage bundles in €/bundle
Q_{tc}	=	The amount of transport capacity contracted in mcm/day
P_{tc}	=	Price of transport capacity in €/mcm/day
C_F	=	Fixed costs

In the long term, a trader can change the variables of its contract portfolio which consists of supply, transport, storage and production contracts. Decision algorithms are used to adjust contracts on the basis of projected demand and past shortages.

4.5.3 Resource operators

A resource operator is characterized by three internal processes: its operation of one or more gas reservoirs, its investment in new reservoirs and its contracting procedure (see Figure 4.6). It is linked to one or more traders by contract or integration and receives daily requests for gas from them. If it has more than one reservoir at its disposal, it uses a preference scheme to decide which reservoirs will produce first.

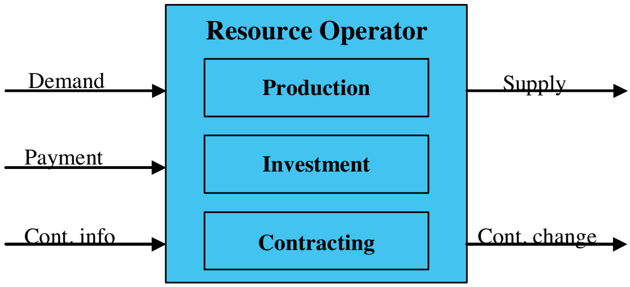


Figure 4.6: The resource operator agent's inputs, internal processes and outputs.

Each reservoir is represented by a physical model containing seven parameters: initial volume, initial pressure, well flow pressure (as a fraction of reservoir pressure), abandonment pressure, reservoir temperature, productivity index and installed production capacity. At the start of the simulation, the reservoir is initialized with regard to volume and pressure. Each day, the current volume is used to calculate current reservoir pressure (see Appendix I for a full derivation).

If reservoir pressure is smaller than the abandonment pressure, the reservoir is abandoned and production capacity is set to zero. This is a physical approximation to the economic decision to abandon the reservoir when production is no longer economical. If reservoir pressure is greater than the abandonment pressure, the difference between reservoir pressure and well flow pressure is multiplied by the productivity index to calculate production capacity.

$$PC_{res} = \begin{Bmatrix} 0 & \textit{if } P_{res} =< P_{ab} \\ \left(P_{res} - P_{wf}\right) \cdot PI & \textit{if } P_{res} > P_{ab} \end{Bmatrix} \tag{4.8}$$

With:

PC_{res}	=	Reservoir production capacity in mcm/day
P_{res}	=	Reservoir pressure in Pa
P_{ab}	=	Abandonment pressure in Pa
P_{wf}	=	Well flow pressure in Pa
PI	=	Productivity index in 1/Pa*day

Actual production capacity is the minimum of calculated production capacity and installed capacity.

$$PC_a = \min(PC_i, PC_{res}) \tag{4.9}$$

With:

PC_a	=	Actual production capacity in mcm/day
PC_i	=	Installed production capacity in mcm/day

Information about production capacities and volumes for each reservoir is used by the resource operator to determine how much each reservoir will produce that day.

Each year, a resource operator can decide to explore for new reservoirs. When detailed information about the subsurface is available, each resource operator can be assigned a number of prospects in addition to its reservoirs. A prospect is similar to a reservoir, but in addition to its reservoir properties it also has a "possibility of success" attached to it. This determines the probability of success when a prospect is drilled. When a resource operator decides to drill a prospect, it pays a sum of money and a random number decides whether the drilling was successful. If so, the prospect will be treated as a reservoir after a certain lead time. The decision to drill is determined by each resource operator's drilling frequency, which represents its level of exploration activity.

Alternatively, a general prospect template can be used in which the proportions of the reservoir properties are set and the size of the reservoir is determined by the resource operator's drilling effort. The drilling effort is in turn determined by a profit maximization process where an increase in drilling activity decreases the possibility of success. The drilling effort will then be set at a level where expected marginal revenue is equal to drilling costs. This approach is preferable when there is little information available about the subsurface.

Finally, a resource operator also decides at what price it sells the gas. In most cases, the common industry practice is adopted of selling the gas at parity with similar oil products. This is known as oil-indexed pricing. However, other pricing strategies can be introduced where they are deemed more appropriate.

A resource operator has an initial stock of money. Each day, its money stock increases with the money received from traders, which is equal to the amount of gas produced multiplied by the oil-indexed contract price for gas. Its stock decreases with the costs made to maintain and operate its facilities. In the case of exploration, a sum of money is subtracted from its money stock for each drill.

$$M_R(t) = M_R(t-1) + \left(Q_{rt} \cdot P_{rt}\right) - \left(C_o \cdot PC_i\right) - E \qquad (4.10)$$

With:

M_R	=	Resource Operator Money stock in €
Q_{rt}	=	Quantity of gas sold in mcm/day
P_{rt}	=	The trader-resource operator contract commodity price in €/mcm
C_o	=	Operating costs in €/day
E	=	Exploration effort in €/day

4.5.4 Storage operators

A storage operator is characterized by three internal processes: the operation of one or more storage facilities, investment in new facilities and contracting out its services (see Figure 4.7). A storage operator injects, stores and produces gas according to customer demand. As such, it does not own the gas it produces, injects and stores. It is linked by contract or integration to one or more traders, who are entitled to produce, inject and store their gas in the facility. A storage facility is modeled as a reservoir, but has some additional features.

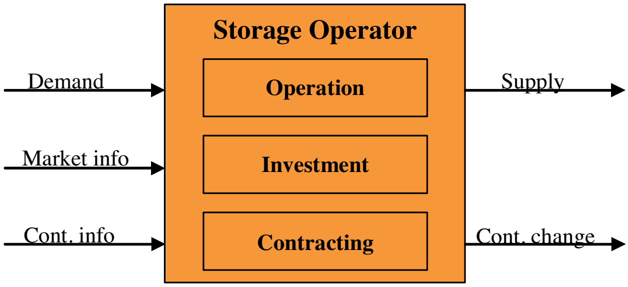


Figure 4.7: The storage operator agent's inputs, internal processes and outputs.

First of all, a facility's injection function is parameterized by an installed injection capacity, an injectivity index and an injection pressure. This enables the calculation of injection capacity as a function of the current volume stored, in a fashion similar to the calculation of production capacity (see § 4.5.3 and Appendix I).

Second, a facility's volume is the sum of its working volume and its cushion volume. The cushion volume is never produced; it is only there to maintain production capacity at an adequate level. Therefore, a facility's contractually available storage capacity is equal to its working volume.

Capacity is sold in one or more 'bundles', consisting of injection, production and storage capacity in a fixed proportion. A storage operator decides how to price the bundles it offers for sale to traders on the basis of its costs and its desired profit rate. The actual price is determined by multiplying the costs made with a markup factor. The markup factor can be input, but it can also be the result of a profit maximizing strategy used by the storage operator.

A storage operator can also invest in a new storage facility. Investment is based on the demand signals received from traders. If demand exceeds the number of bundles available, the storage operator will invest in extra capacity. New facilities are modeled in a way similar to prospects. They have to be defined and ascribed to the storage operator at the start of the simulation. Investment changes their status from non-operational to operational. Two types of investment decisions are distinguished: those made solely on the basis of demand expectations, and those underpinned by contracts.

In the first case, investment is more risky, because expectations can be wrong. In the second case, a so called open season is held, which ends with the forward sale of capacity, after which investment can take place more or less risk-free.

A storage operator has an initial stock of money. Each day, its money stock increases with the money received from traders for the usage of its facilities. Its stock decreases with the costs made to maintain and operate its facility and possible investment costs.

$$M_S(t) = M_S(t-1) + \left(Q_{sb} \cdot P_{sb}\right) - \left(C_o \cdot Q_{sf}\right) - C_i \tag{4.11}$$

With:

M_S	=	Storage operator money stock in €
Q_s	=	Quantity of storage capacity sold in mcm
P_s	=	The price of storage capacity in €/mcm
C_o	=	Operating costs in €/day
Q_{sf}	=	Number of storage facilities operated
C_i	=	Investment costs in €

4.5.5 Network operators

A network operator is characterized by three internal processes: the operation of one or more transmission networks, investment in additional transport capacity and contracting out its services (see Figure 4.8). As with the storage operator, a network operator does not transport its own gas, but transports traders' gas on their behalf. A network operator sells transport capacity to traders in their role of shipper. In addition, a network operator is linked to either a resource operator, a storage operator or the spot market for balancing the network's input and output.

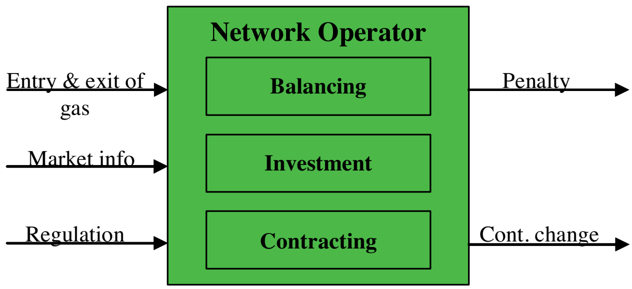


Figure 4.8: The network operator agent's inputs, internal processes and outputs.

Each network is represented by a physical model, which has a certain shape and size. The shape of the physical network is shown in Figure 4.9. The network has a number of entry points, a number of exit points, and an amount of transport capacity connecting them. Entry points connect resource operators, other networks (import or domestic) and storage operators (for production purposes) to the network, whereas exit points connect users and storage operators (for injection purposes) to the network. Since building transport capacity is more expensive than building entry or exit capacity, it is usually the smallest of the three and thereby the limiting factor for transport. A network's size is therefore equated to its transport capacity. In addition, the network can serve as a platform for trade. Gas inside the network is also considered to be inside a virtual hub, where it can be traded among shippers. However, for trade to be possible, an institutional agent such as a spot market agent is required in addition to the network operator agent.

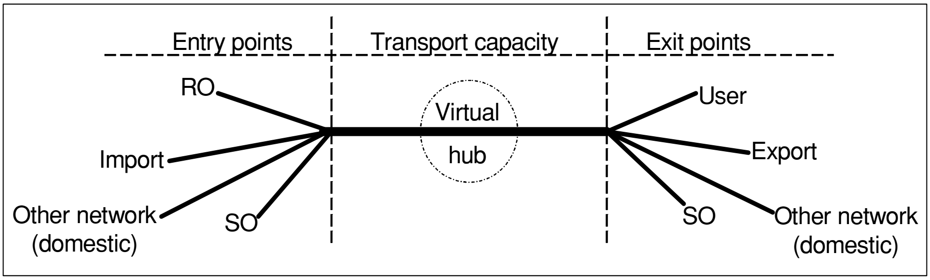


Figure 4.9: The shape of a network operator's physical network.

Each day, the network operator compares the gas taken from the network with the gas delivered to the network. If the two are unequal, the network operator balances the two with the help of its buffer facility and fines the trader which is responsible a penalty proportional to the imbalance. Whether it is successful in balancing the network each day or not is expressed in a binary variable called "system integrity", which is the ultimate measure of a supply interruption. In the case of an interruption, network pressure drops below the minimum allowed, supply is interrupted, and users receive only a random fraction of the gas they demanded.

It is often the case that one network is linked to another. If a network operator operates two or more linked networks, it can sell transit capacity as well. Another possibility is that two linked networks are operated by two different network operators. In that case, the owner of the transit pipeline sells the capacity. A special case can be found in the Netherlands, where two networks are linked that transport different qualities of gas. This means gas can only flow from the high quality network to the low quality network and only after passing through a blending station which lowers the gas quality. In such a case, blending capacity functions and is sold in a manner similar to transit capacity.

A network operator has a decision algorithm for investing in additional transport capacity. It does so based on demand signals from traders. If demand exceeds available transport capacity, the network operator invests and transport capacity is increased with an amount equal to the excess demand or a minimum threshold for

investment, whichever is higher. As with the storage operator, a network operator can be programmed to invest only after holding an open season.
A network operator cannot decide freely how to price the capacity it sells, as its profits are regulated. This is represented by imposing a regulated profit margin on the network operator. The actual price is then determined by multiplying its costs with a markup factor.

A network operator has an initial stock of money. Each day, its money stock increases with the money received from traders and users for the use of its facilities. In addition, its money stock decreases with the costs made to maintain and operate its facility. In the case of an unbalance, the network operator incurs costs for buying gas from its buffer source and receives money from traders by penalizing them for their unbalance. If system integrity is breached, the network operator incurs 'integrity costs' for restoring the network pressure and compensating affected parties.

$$M_N(t) = M_N(t-1) + \left(Q_{tc} \cdot P_{tc}\right) + U - \left(C_o \cdot TC\right) - C_b - C_{inv} - C_{\text{int}} \qquad (4.12)$$

With:

M_N	=	Network operator money stock in €
Q_{tc}	=	Amount of transport capacity sold in €/mcm/day
U	=	Unbalance penalties in €
C_o	=	Operating costs in €/day
TC	=	Amount of transport capacity available in mcm/day
C_b	=	Buffer costs in €
C_{inv}	=	Investment costs in €
C_{int}	=	Integrity costs in €

4.5.6 Integration

The Integration agent is designed to describe the relation between actor agents which are part of a single company. Integration has several consequences for the flows of information, gas and money between integrated actors. Information transfer between integrated actors is assumed to be complete, gas flow is still physically constrained but no longer contractually, and money stocks are merged, so no internal money flows are necessary. Furthermore, the actor agents' separate contracting algorithms are replaced with a single algorithm covering both agents (see Figure 4.10). In addition to these changes, some behavioral adjustments can be introduced. In general, behavior is adjusted in such a way that the money stock of the whole company is maximized rather than that of the individual actor agent.

First of all, agents in a buyer-seller relationship may confer preferential treatment upon each other. For example, In the case of a trader integrated with a storage operator, the trader may prefer storing gas in its own facilities over storing it in cheaper facilities owned by others. Similarly, a storage operator may offer only that capacity on the market which is not needed by the trader it is integrated with.

Second, obligations to demand or deliver may be treated more flexibly. For example, a trader integrated with a user does not have a contractual obligation to deliver, and may therefore be allowed to deliver less than is demanded. Similarly, a trader integrated with a resource operator may accept less gas than is offered.

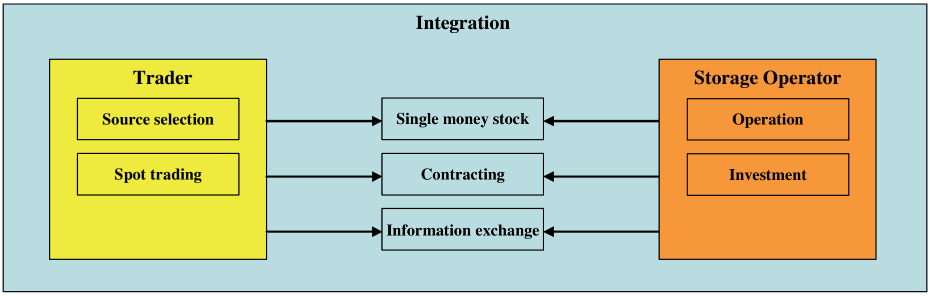


Figure 4.10: The integration agent connecting a trader agent and a storage operator agent.

4.5.7 Contracts

Contract agents are a relatively rigid form of relation between actor agents. A contract contains a number of provisions that have to be complied with by both parties. The flow of information between actor agents is limited, as they only receive the information about the counterparty which is contained in the contract, and no information about physical states or other internal processes. A contract is treated as a separate agent, in the sense that it is modeled as an individual set of state variables with its own information flows and its own decision algorithm, which represents the bargaining process between actors (see Figure 4.11).

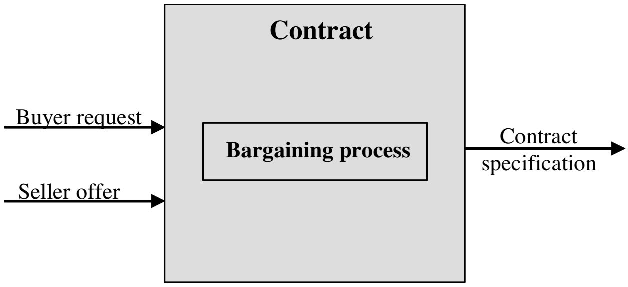


Figure 4.11: The contract agent's inputs, internal processes and outputs.

Each contract has a duration, during which no changes can be made to its variables. When the contract expires, a process of renegotiation starts. The outcome of the negotiation determines the values of the contract variables for the next contract period. In general, prices are determined by the selling party, whereas quantities are the minimum of both contract parties' desired quantities. When aggregated demand is greater than supply and there are multiple buyers, the available quantity is distributed among buyers proportional to their demand. It should be noted that actor agents can be connected through a contract agent with a contract value of zero. This enables agents to start and stop contracts throughout the simulation.

There are four types of contract available in the ENETSIM library, each with its own provisions.

- The supply contract specifies the maximum amount of gas per time unit a buyer is entitled to demand, the price at which the gas is sold (commodity price) and the fixed tariff paid for the maximum allowed offtake (capacity price).
- The production contract is a more elaborate version of the supply contract, and specifies three variables which determine the quantity and two variables which determine price:
  - The Take Or Pay (TOP) quantity is the amount of gas per time unit a buyer has to pay for, whether he physically receives the gas or not;
  - The Daily Contract Quantity (DCQ) is the average amount of gas per time unit a buyer agrees to purchase;
  - The Swing factor is a number ≥ 1 which, multiplied by the DCQ, represents the maximum amount of gas per time unit the seller is required to supply, i.e. the production capacity it should have at its disposal.
  - The commodity price determines the unit price for gas;
  - The capacity price determines the fixed tariff paid for the maximum allowed offtake.
- The storage contract specifies the amounts of injection capacity, storage capacity and production capacity the buyer has at its disposal. The three types of capacity are sold and bought together in the form of bundles. This means the relative magnitude of each variable is constant. The contract also specifies the price and size of the bundle.
- The transport contract specifies the amount of transport capacity at the trader's disposal for shipping purposes and the price at which capacity can be bought.

Additional contract types are possible, such as:

- A network exit contract, specifying the amount of gas per time unit a buyer is allowed to withdraw from the network, i.e. its exit capacity;
- A network entry contract, specifying the amount of gas per time unit a buyer is allowed to send into the network, i.e. its entry capacity;

However, these are currently not included in the model as they are assumed to be of limited importance.

The standard duration of a contract is one year. Supply, production and transport contracts start and end on the 1st of October, in accordance with the user demand curve described in § 4.5.1. The storage contract starts and ends on the 1st of April. This allows storage users to inject gas into their newly bought capacity from April to September, and then produce it from October to March, leaving them with an empty storage at the end of the contract year.

4.5.8 Markets

Finally, a market agent represents the most distant type of relation between actors. In principle, two types of product lend themselves best to market trading: gas as a commodity and the capacity to transport it. There are also two types of market: a spot market and a term market. The spot market facilitates the trade of gas to be delivered immediately, whereas a term market facilitates the trade of gas to be delivered over one or more weeks, months or longer periods. At present, the library contains only a commodity spot market. Trade in capacity is either impossible or rare in current EU markets and term markets are substituted for by contract agents.

The commodity spot market is modeled as follows. Each trader can submit one or more bids and/or offers. A bid consists of a bid quantity of gas to be bought at any price up to the bid price. An offer consists of an offer quantity of gas to be sold at any price higher than or equal to the offer price. From these bids and offers, demand and supply curves are constructed. A market clearing process then ensues, the result of which is an allocation of supplies to bidders at the market clearing price (see Figure 4.12). As the market clearing process is assumed to take place within a day, the process is not modeled explicitly. The equilibrium resulting from all bids and offers is calculated instead.

Given the trader's preference scheme (see § 4.5.2), its activity on the spot market can be modeled as a combination of two bids and one offer, which are:

- A "base bid", which aims to substitute supply from a contract with less expensive supply from the spot market;
- A "peak bid", which aims to add supply from the spot market to supply from a contract in the case of a shortage;
- An offer, which aims to sell available supply from a contract at a price above the contract purchase price.

Figure 4.12: The spot market agent's inputs, internal processes and outputs.

4.6 Data requirements

Each model must be made operational with a dataset. This dataset contains the initial value of each state variable, as well as the value of each system parameter. Some data is specific to an agent, other data is general to the model. The complete list of variables and parameters is provided below.

- General model data consists of the model's runtime, the initial value and development of the oil price over time, the initial value and development of temperature over time and the state of the subsurface with regard to exploration;
- Each contract agent requires initial values for its variables and a duration parameter;
- Each actor agent requires an initial value for its money stock and a measure of its risk tolerance (either a contracting safety margin or an investment threshold);
- Each actor agent operating physical infrastructure (resource operator, storage operator and network operator) requires parameters for the physical characteristics of its infrastructure, initial values for the state of its infrastructure, and values for the operating costs and investment costs of its infrastructure;
- Each actor agent using a markup (trader, network operator and storage operator) requires one or more parameters determining the markup;
- Each user agent requires parameters determining its income, average demand, seasonality of demand, degree of random fluctuation, switching propensity, price sensitivity, and costs of supply interruption;

4.7 Verification and validation of ENETSIM models

When ENETSIM models are used to draw conclusions about the functioning of the natural gas market and the implementation of energy policy, it should be clear what value can be assigned to model results. In other words, the reliability of ENETSIM models and of the results they generate should be assessed. In the literature addressing this issue, two forms of reliability testing are generally distinguished: verification and validation (Kleijnen, 1995). This section discusses both concepts and how they apply to ENETSIM.

Essentially, verification is about ensuring that a simulation model behaves as the programmer thinks it does. When it does not, it means there is a 'bug' in the program which should be removed. In other words, verification's sole concern is the perfect correspondence of a model to the programmer's image of it. This can be achieved by a continuous process of running a model, interpreting the results, implementing a change, running the model again, etc. In the case of surprising results, the model should be analyzed until the source of the unexpected result is found.

A related concern is how to communicate the verity of a simulation model to others. Although, formally, every simulation result is a strict deduction, the deductive steps leading to the conclusions are not as clear as in traditional economic models (Epstein, 2006). Therefore, care should be taken that a simulation model's structure is communicated in such a way that all steps in the deductive process are well understood. This prevents readers from seeing a model as a 'black box' and questioning its verity. A method for testing whether such communication is adequate is suggested by Axelrod (2003), which is to let an independent researcher reproduce a model's structure and results on the basis of the model description.

In this study, model verity is communicated by presenting a series of initially simple models with gradually increasing complexity, combined with a detailed explanation of the results. This process occupies most of Chapter 5. The reproduction of ENETSIM models and their results by an independent researcher could be attempted in the future on the basis of this thesis.

Validation, the second reliability criterion, is concerned with the correspondence of a model to the system (i.e. the part of reality) under study. When sufficient data are available, a model can be validated by using it to replicate historical output. This process is known as descriptive output validation. If this is successful, the next step is predictive output validation, which requires generating a (successful) prediction about the behavior of the system before the behavior takes place. When a model is to be used for projections into the future (which cannot yet be tested), the model can only be calibrated, which is done by matching output with the present situation. The model is then used to extrapolate the current situation to the future.

Performing a full output validation process for each ENETSIM model is beyond the scope of this study. Therefore, rather than focusing on absolute output values, validation in this study is limited to looking at the sign of changes in output as a function of changes in input, i.e. a model's set of partial derivatives. Results obtained in this manner should either be in line with established theory or be made plausible by explaining why they depart from it. Such a sensitivity analysis can be performed by adjusting a single parameter or decision algorithm at a time. Alternatively, a scenario analysis can be performed, in which case an attempt is made to identify the relevant uncertainties underlying a model and then to define a scenario as a consistent storyline where the value of each uncertain parameter or relation is assigned a value in accordance with the storyline. This provides insight into the impact of model uncertainty as a whole rather than of individual parameters and relations.

As described in Chapter 3, the ENETSIM framework in itself is a kind of sensitivity analysis with regard to the equilibrium models prevalent in the literature. By introducing market imperfections into a model of the natural gas market, the sensitivity of results to these market imperfections is ascertained. The ENETSIM framework is also subjected to a variety of sensitivity analyses with regard to its own input. Together, these analyses should provide a degree of validity to the framework.

In the remainder of this study, a number of simulations will be performed with the ENETSIM framework. Chapter 5 presents a series of models ranging from the very basic to the reasonably complex. This mimics the verification process undertaken for the methodology as a whole. In Chapter 6, the effect of liberalization on energy policy goals is analyzed. This is done by developing two models, one of which is structured as a pre-liberalization market, the other as a post-liberalization market. The comparison of both models tests the sensitivity of results to a change in market structure. In addition, both models are subjected to an additional sensitivity analysis with regard to the value of individual parameters. Finally, Chapter 7 consists of a scenario analysis. It uses the post-liberalization model from Chapter 6 to explore three scenarios for the future of the Dutch market. This is a test of the sensitivity of results to simultaneous changes in groups of parameters and decision algorithms.

An additional, novel validation method, called "iterative participatory modeling", is employed to validate ENETSIM in Section 5.6. This approach is based on the active involvement of the intended users of the model and/or those being modeled (Barreteau, 2003). In other words, this method shifts attention from the data generated by a system to the people constituting the system. By involving them in the modeling process, a feedback loop between a model and real life subjects is created. This may even take the form of human subject experiments, the results of which can be transferred to the simulation model. This procedure doubles as a tool for training and education, as it allows participants to explore the structure of the system and test the effects of their decisions and behavior on outcomes (Axelrod, 2003). In this study, validation through iterative participatory modeling has been performed with students. Participation by industry stakeholders could provide further validation in the future.

5. Some applications of the ENETSIM framework

5.1 An elementary natural gas market model

In this chapter, some exemplary models are developed to clarify the descriptions given in the previous chapter, explore their implications and derive some basic results. The strategy employed is to start simple and then gradually add complexity.

The simplest way imaginable to model a natural gas market (assuming producer and consumer are not integrated) is to attribute demand to one user agent (named consumer), attribute supply to one resource operator agent (named producer) and connect them with a supply contract agent, as shown in Figure 5.1. This model will be called Gasnet1.

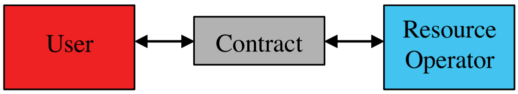


Figure 5.1: Gasnet1, an elementary natural gas market model.

The actual Simulink model represented by this diagram is shown in Figure 5.2.

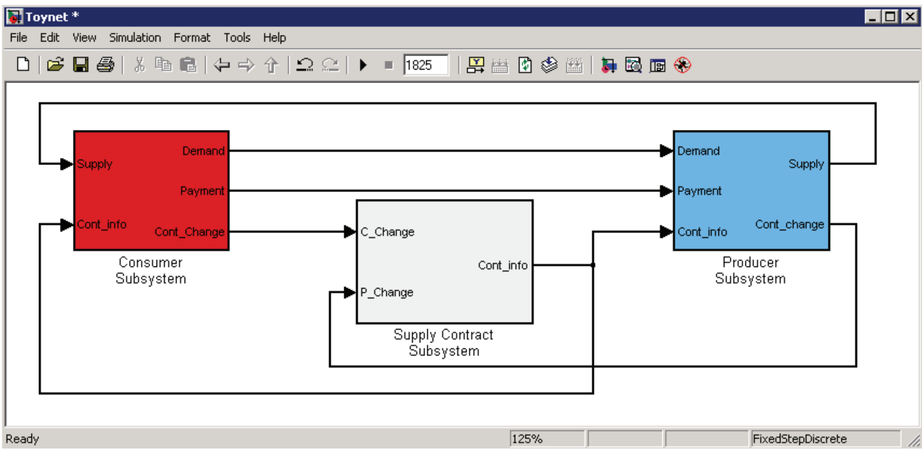


Figure 5.2: A screenshot from an actual Simulink model corresponding to the diagram in Figure 5.1.

As can be seen in Figure 5.2, each agent takes the form of a subsystem, which is a smaller Simulink model that is itself part of the main model. The consumer subsystem and producer subsystem are shown in Figure 5.3. Both subsystems consist of several subsystems themselves. These subsystems roughly correspond to the general functions performed by each agent as shown in Figures 4.4 and 4.6.

The user agent's demand subsystem generates demand and its contracting subsystem determines the user's desired contract specification. In more advanced models, the contracting subsystem also determines a user's switching behavior. Consumption is not explicitly modeled, but is implicitly included as the removal from the system of all gas which enters the consumer subsystem.

The resource operator agent's production subsystem contains a physical module of a producing reservoir, which determines supply (as a function of demand) and production capacity. In addition, the timing and magnitude of its investment in new reservoirs is determined here. The contracting subsystem determines the producer's desired contract specification. Part of this contract specification is the price of gas, which is also determined by the producer in his contracting subsystem.

In addition to these functions, both agents have a financial subsystem which is used to keep track of each agent's income, costs, payments and resulting money stock.

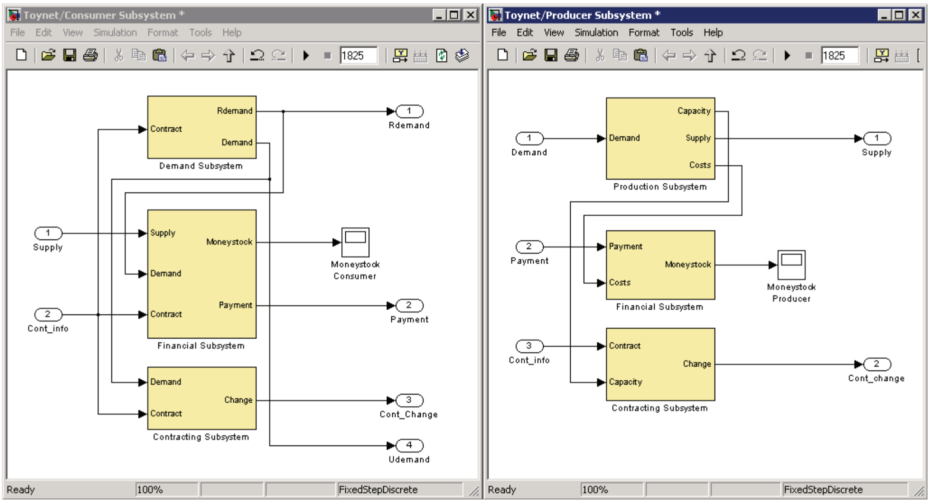


Figure 5.3: Contents of the consumer and producer subsystems.

The short term dynamics in such a model are shown in Figure 5.4, with black arrows representing information flows, green arrows representing gas flows and purple arrows representing monetary flows. Long term dynamics involve changes in the contract parameters as well as investments by the resource operator in new reservoirs.

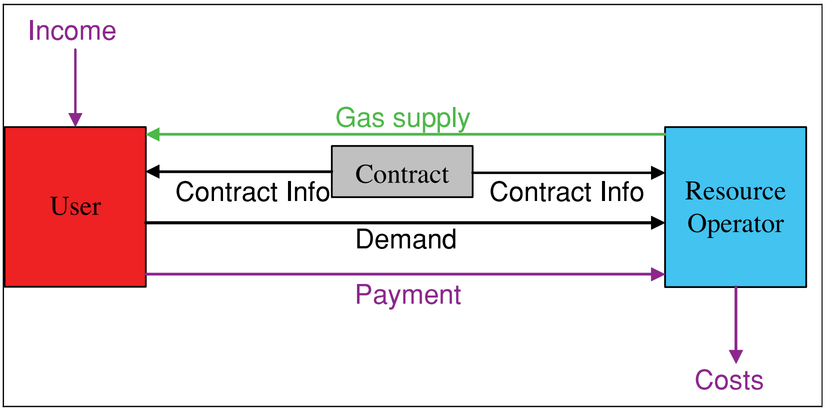


Figure 5.4: Short term dynamics in an elementary natural gas market model.

With the agent network set, the next step is to choose the agents' decision algorithms. For the user, these are demand generation and contracting, for the contract, this is only the bargaining process, and for the resource operator, these are production, investment, and contracting. Each is briefly described below.

- Demand generation: the annual base level of demand is assumed to be constant, which means demand is a function of temperature, price sensitivity and a random component (see Eq. 4.2).
- Contracting: since there is only one supplier, no switching takes place and only the absolute level of contracting is relevant. This level is equal to the maximum historical demand in memory multiplied with a safety margin (>1).
- Bargaining: the bargaining process is modeled as follows: the seller determines price and the maximum quantity sold, and the buyer determines the quantity bought at or below the maximum.
- Production: the resource operator divides demand over his producing fields proportional to production capacity, i.e., if a field's production capacity is 10% of total capacity, 10% of demand is allocated to it.
- Investment: once a year, the exploration effort is determined. The amount invested is the minimum of exploration capacity and the profit maximizing amount of exploration.
- Contracting: the resource operator links commodity price to the oil price and sets capacity price at operational cost times a capacity margin. The quantity to be sold is equal to production capacity multiplied with a safety margin (<1).

Table 5.1: Dataset for the elementary natural gas market model.

Name	Description	Value
<u>*General data:*</u>		
Runtime	Simulated time	730 days
Tempav	Average temperature	9.75 °C,
Tempdev	Maximum deviation from average (sine curve)	7.25 °C
Expfactors	The exploration cost curve (intercept, gradient)	3, 3
Oilindexedprice	Price of oil (constant over simulation period)	150 € / mcm
<u>*User data:*</u>		
Udemand	Temperature sensitivity, Average demand	14 mcm/K, 250 mcm/day
Umoneyinit	User's initial money stock	0 kE
Udamage	Costs incurred for non-satisfied demand	200 kE/mcm
Uincome	User income	48000 mcm/day
Ucsm	Capacity contracted above expected need	1.02
<u>*Contract data:*</u>		
CP	Maximum demand allowed, Commodity price, Capacity price.	325 mcm/day, 150 kE/mcm, 15 kE/mcm
Duration	Time between renegotiations	1 year
<u>*Resource op. data:*</u>		
Rres1	Volume, Initial volume, Initial pressure, Well flow pressure, Abandonment pressure, Reservoir temperature, Productivity index, Installed capacity.	$2*10^6$ mcm, $2.5*10^6$ mcm, $4*10^7$ Pa, 0.25, $4*10^6$ Pa, 313 K, $8*10^{-8}$, 400 mcm/day.
Prospect	Initial volume, Initial pressure, Well flow pressure, Abandonment pressure, Reservoir temperature, Productivity index, Installed capacity.	3000 mcm, $4*10^7$ Pa, 0.25, $4*10^6$ Pa, 313 K, $7.5*10^{-10}$, 1 mcm/day.
Rmoneyinit	Resource operator's initial money stock	0 kE
Rcapmargin	Margin made on capacity sales	0.2
Rcosts	OPEX	75 kE/day
Rinvcosts	CAPEX	10000 kE/mcm
Rinvmargin	Required return on investment	1.1
Rlead	Lead time	1 year
Rmaxinv	Exploration capacity	0 mcm/year
Rcsm	Fraction of existing capacity contracted out	0.98

Finally, the model also includes a dataset, specifying the values of agent variables and parameters, as well as some general system parameters. The complete list for the elementary model is provided in Table 5.1. The datasets of all models used in this chapter are reproduced in Appendix II. The values are chosen somewhat arbitrarily.

As the model does not aim at describing any natural gas market in particular, values are chosen solely with the purpose of obtaining some indicative results.

5.2 Results from the elementary model

Running the model with the agent network, decision algorithms and data described in the previous section yields the following results. First of all, the agent-level output from the model comprises the actor agents' money stocks and the contract variables. These are shown in Figure 5.5. The money stocks are shown in the left hand graph. Both stocks increase over time, indicating that the user's income is on average higher than its expenses and the resource operator's revenues are on average higher than its costs. The gradients of both lines vary, because of the seasonality of demand. In winter, demand is high, so the user's money stock decreases and the resource operator's money stock increases. In summer, the opposite applies.

The contract variables are shown in the right hand graph. The duration of the contract is one year, so in a two year simulation the variables can change value only once. In this model, prices stay constant, as the commodity price depends on the oil price and the capacity price depends on operational costs, both of which are constant. The quantity does change after one year, because the initial contract quantity specified in the dataset is lower than the user's actual demand.

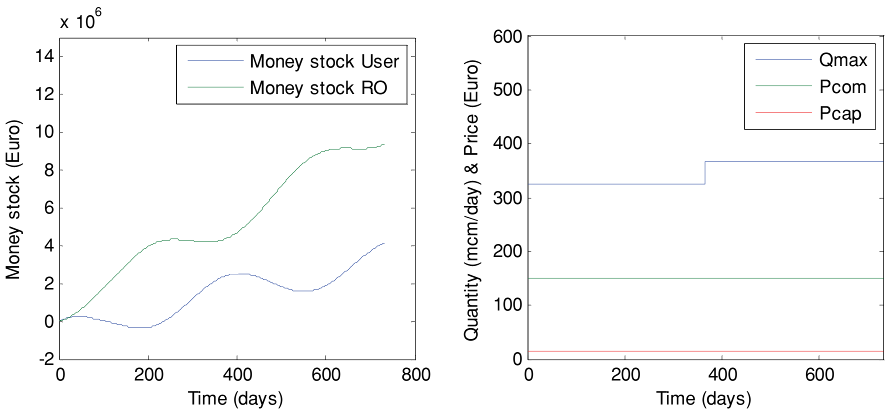


Figure 5.5: Agent-level output: money stocks and contract variables.

The discrepancy between user demand and the initial contract can also be seen in Figure 5.6, top-left. In this figure, the system-level model output is plotted, which can be used to determine affordability and supply security. The top-left graph shows three variables used to evaluate the first two security conditions: D, S_c, and S_d. (In this case, S_c and S_d are equal, so only two lines are visible.)

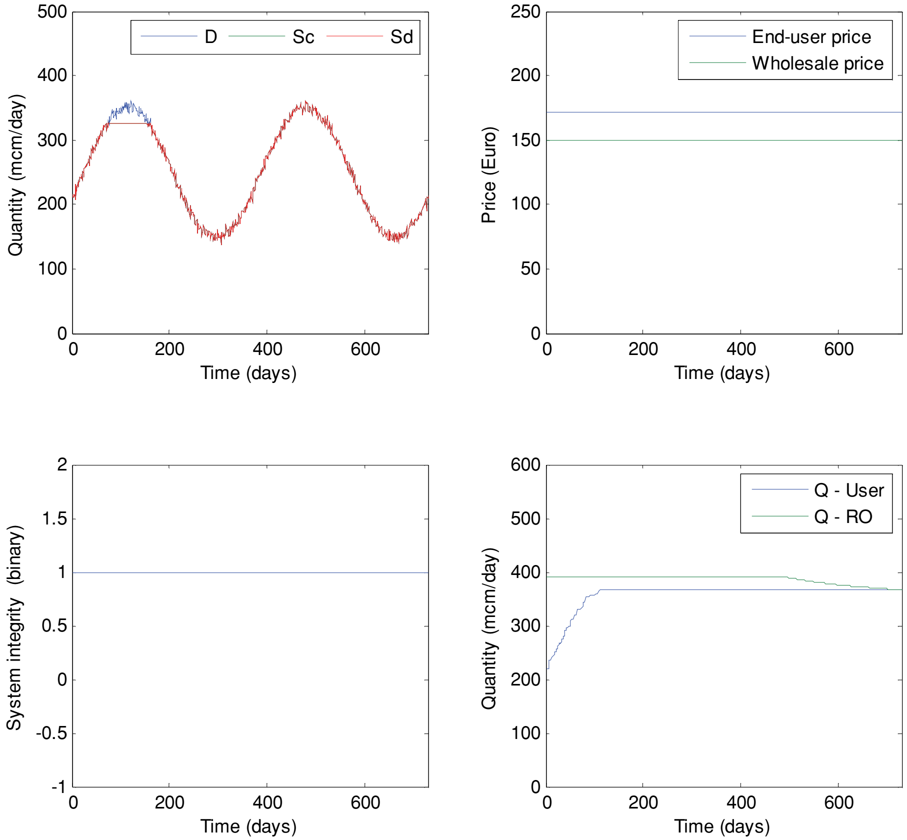


Figure 5.6: System-level output: affordability and supply security.

Average end-user price	=	171.1 kE/mcm
Quantity condition not met	=	83 out of 730 days
Physical condition not met	=	0 out of 730 days
Price condition not met	=	0 out of 730 days

As the physical condition depends on the equality of S_c and S_d, this condition is met. Whether S_c and S_d are exactly equal can be hard to see, so the bottom-left graph is added to show a binary signal (system integrity) which is equal to one when S_c and S_d are equal, and zero otherwise. When a network operator agent is included in the model, the system integrity variable is automatically included as its agent-level output.

In year one, the contract constrains supply, so $D > S_d$ in the three winter months. In year two, the contract has been changed, and all variables have the same value continuously. In other words, the quantity condition is only satisfied in the second year. The quantities offered and requested in the contract are shown in the bottom-right graph. The quantity offered is a function of the resource operator's production capacity. In the second year, production capacity starts to decline, and therefore the quantity offered does too. The quantity demanded is a function of the user's past demand. Therefore, it only reaches its peak after the first winter has passed.

Finally, the price condition can be inferred from the top-right graph, which is also used to determine affordability. The graph shows both the wholesale price (which in this case is equal to the contract commodity price) and the end-user price, which includes the commodity and capacity price with an appropriate weighting. These graphs can be summarized by using the average end-user price as a proxy for affordability and the number of days each security condition is (not) met as a proxy for supply (in-) security. To assess the price condition, a maximum acceptable price must be imposed, which can, for example, be set equal to a user's daily income divided by its average demand, yielding a price of 192 kE/mcm (see Table 5.1). For Figure 5.6, this leads to the following results:

Next, the simulation runtime can be extended from two to five years by changing the value of the "runtime" parameter in the dataset from 730 to 1825. Figure 5.7 shows the processed output from this run. Keeping in mind that there is no investment in this scenario, it is clear that problems will occur. The bottom-right graph shows production capacity declining continuously, increasing the gap between supply and demand. The top-left graph shows the consequences of this increasing gap. In years four and five, the contract quantity has decreased. This manifests itself in a gap between D and S_c. In addition, a gap develops between S_c and S_d. This is caused by the structure of the resource operator's contracting decision algorithm, which (in this example) does not take into account the decline in production capacity during the year. This gap is also visible in the bottom-left graph, in which system integrity is zero when such a gap occurs. This graph shows that the physical condition is violated in year three as well. The results from Figure 5.7 can again be summarized by the numbers provided below the graphs.

The average end-user price is unchanged, which means the price condition is still met continuously. However, the number of days the quantity condition and physical condition are not met has increased significantly. The number of days the quantity condition is not met rises with 221 days, whereas the number of days the physical condition is not met rises with 232 days. The quantity condition is still breached more often than the physical condition, which is a consequence of the low initial value of the contract quantity. However, the difference is smaller than in the previous model run, because of short periods where the contract quantity is adequate but physical supply is not.

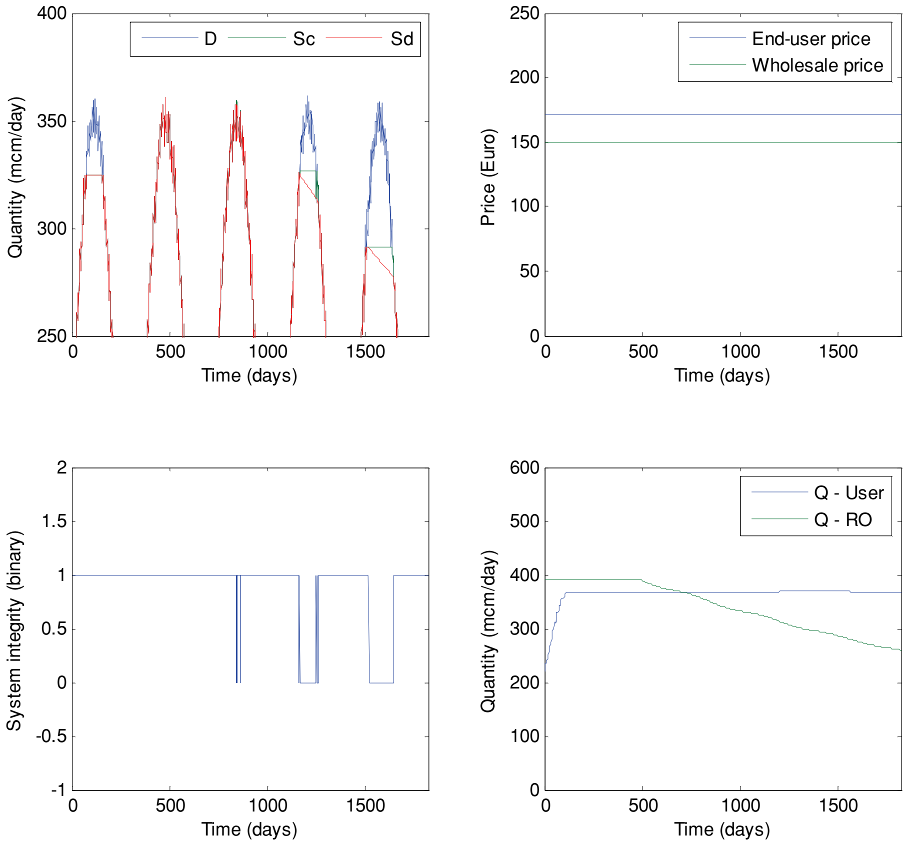


Figure 5.7: System-level output for the extended model run.

Average end-user price	=	171.1 kE/mcm
Quantity condition not met	=	304 out of 1825 days
Physical condition not met	=	232 out of 1825 days
Price condition not met	=	0 out of 1825 days

When investment is introduced in the model by raising "Rmaxinv" in the dataset from 0 to 30, this problem disappears. The left hand graph in Figure 5.8 shows the Resource operator's production per field. The original field is still in decline (dark blue line), but new fields come online each year (other lines). The new production capacity compensates for the decline and total capacity remains at an adequate level. The development of total available production capacity is shown in the right hand graph. This parameter change restores output indicators to their previous level, as shown below.

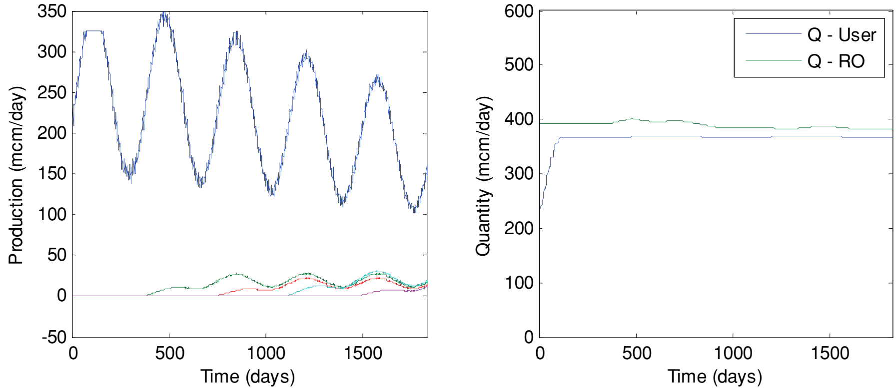


Figure 5.8: Development of production capacity after the inclusion of investment.

Average end-user price	=	171.1 kE/mcm
Quantity condition not met	=	83 out of 1825 days
Physical condition not met	=	0 out of 1825 days
Price condition not met	=	0 out of 1825 days

From a supply security perspective, the model runs discussed above focus only on internal risk. It is possible to analyze external risks by including some additional parameters in the model. To conclude this section, a scenario is created which includes two additional parameters: "cold winter" and "interruption". The "cold winter" value is subtracted from the average temperature, thereby increasing demand while preserving the shape of the curve. This is useful for studying external weather risk. The "interruption" parameter describes three things: the first day supply is interrupted, the last day supply is interrupted, and the severity of the interruption (1 = no interruption, 0.5 = facility 50% offline, etc.). In addition, one or more facilities must be chosen to which the interruption applies.

As an example, the sensitivity to external risks of the model described above is tested. To this end, a few adjustments to the model are made. "Runtime" is set to 365, so only one year is simulated. The contract quantity is set to 450 mcm/day, to make sure it is not a limiting factor. The interruption is set to last from day 150 to day 160. Then, "cold winter" is varied over a range of 0 to 5 and the severity of the interruption is varied over a range of 1 to 0.5. In this setting, the only viable interruption target is the resource operator's single reservoir. The relevant output of each run is system integrity. 121 (=11*11) Runs are performed to determine the sensitivity of system integrity to these external risks. The number of days the physical condition is not met for each parameter combination is shown in Table 5.2. If the probability distribution of both parameters is known, the overall probability of a security breach can be calculated on the basis of these results.

Table 5.2: A sensitivity analysis of the physical condition with regard to cold winters and supply interruptions.

	Interruption										
Cold winter	1	0.95	0.9	0.85	0.8	0.75	0.7	0.65	0.6	0.55	0.5
0	0	0	0	1	11	11	11	11	11	11	11
0.5	0	0	0	5	11	11	11	11	11	11	11
1	0	0	0	7	11	11	11	11	11	11	11
1.5	0	0	1	11	11	11	11	11	11	11	11
2	0	0	5	11	11	11	11	11	11	11	11
2.5	0	0	7	11	11	11	11	11	11	11	11
3	2	3	13	13	13	13	13	13	13	13	13
3.5	13	18	24	24	24	24	24	24	24	24	24
4	41	48	52	52	52	52	52	52	52	52	52
4.5	65	75	75	75	75	75	75	75	75	75	75
5	77	83	83	83	83	83	83	83	83	83	83

In conclusion, it is evident that even this elementary ENETSIM model has a number of properties not found in most other models. The empirically observed phenomena represented here are:

1. The linkage of the consumer price to the oil price;
2. The structure of a supply contract, which sets rights and obligations in advance of consumption over a prolonged time;
3. The peculiarities of the exploration process, with its limited connection between gas price, exploration effort, and production capacity;
4. The influence of external disturbances, such as low temperatures and facility outages, on supply and demand;
5. The physical inverse relation between the amount of gas produced and the remaining production capacity in a reservoir;
6. Supply insecurity, i.e. the possibility of supply not matching demand.

5.3 Expanding the agent network: traders, integration and the spot market

The model from the previous section can be made slightly more complex by introducing a trader that functions as an intermediary between user and resource operator. The supply contract connecting user and resource operator now connects trader and resource operator, and an additional supply contract connecting user and trader is added to the model. This expanded model is called Gasnet2. The corresponding agent network is shown in Figure 5.9. In addition, a small expansion of the dataset is required, shown in Table 5.3. The complete dataset for this model is provided in Appendix II.

Figure 5.9: Gasnet2, a natural gas market model including a trader.

Finally, some new decision algorithms must be programmed. The bargaining algorithm used in the new contract is taken from the original contract. The trader agent has three decision algorithms: source selection, spot trading, and contracting (see § 4.5.2). Source selection is quite simple, because the trader's only source is the resource operator. Spot trading is not possible, because there is no spot market agent incorporated in the agent network. Therefore, the main issue is how to define the contracting algorithm, with regard to both quantity and price.

Table 5.3: Additional model data.

Name	Description	Value
Tmoneyinit	Trader's initial money stock	0 kE
Tcommargin	Purchase price * commodity margin = commodity price	1.05
Tcapmargin	Purchase price * capacity margin = capacity price	1.05
TCfixed	Fixed costs	100 kE/day
Tcsm	Excess capacity bought	1.02
UT	User-trader contract (Qmax, Pcom, Pcap)	350 mcm/day, 157.5 kE mcm, 15.75 kE/mcm

Price is determined in a straightforward manner. Selling price is set equal to the purchase price times a margin. Determining the quantity is more complex. The trader has to balance the user's demand with the resource operator's supply. To do this successfully, it needs to make projections about the future development of both. In this example, it is assumed that the trader projects a 2% increase in demand per year (as compared to the initial contract) and sufficient overcapacity on the part of the resource operator to accommodate this expansion. The quantity offered to the user and the quantity requested to the resource operator are both based on this projection (see Eq. 5.1).

$$Q_R = Q_{U_{Y-1}} * T_{csm} \quad \& \quad Q_U = Q_R \qquad (5.1)$$

With:
Q_R = Quantity requested by the trader to the resource operator
Q_U = Quantity offered by the trader to the user
T_{CSM} = Trader's contracting safety margin

Figure 5.10 shows some results for this model. The left-hand graph shows how supply slowly catches up with demand, while the left-hand graph shows the contracted quantity in the user-trader contract. The performance indicators show that the end-user price has increased, which is due to the margin added by the trader. The quantity condition is breached more often, because the contract quantity offered increases more slowly.

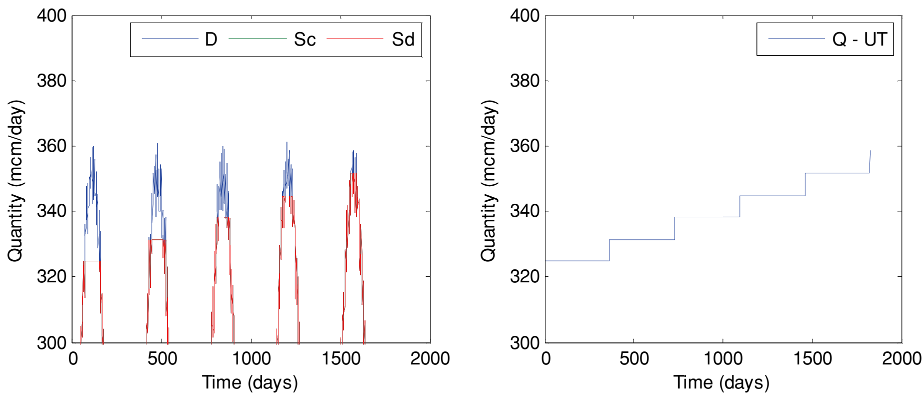


Figure 5.10: Balancing of supply and demand by an intermediate trader.

Average end-user price	=	179.6 kE/mcm
Quantity condition not met	=	271 out of 1825 days
Physical condition not met	=	0 out of 1825 days
Price condition not met	=	0 out of 1825 days

Alternatively, the trader may be more adventurous and plan a 10% per year increase in sales (Tcsm = 1.1). If, at the same time, the resource operator expects a decline in production capacity and offers to sell only 90% of current capacity, a mismatch will occur. Figure 5.11 shows the results for these changes in the dataset. The top-left graph shows how supply initially catches up with demand very quickly, but starts to decline again in later years. The bottom-left graph shows how this leads to several breaches of system integrity. The bottom-right graph shows the contract quantities desired by the user and resource operator, while the top-right graph shows the resulting quantities actually contracted after mediation by the trader.

The average end-user price and the fulfillment of the price condition are unchanged, but the quantity and physical condition are affected by these changes. As the contract quantity offered by the trader to the user now increases faster, the quantity condition is fulfilled more often. However, the failure to match this offer with physical supplies causes the physical condition to be fulfilled less often, implying a tradeoff between fast contract growth and physical security.

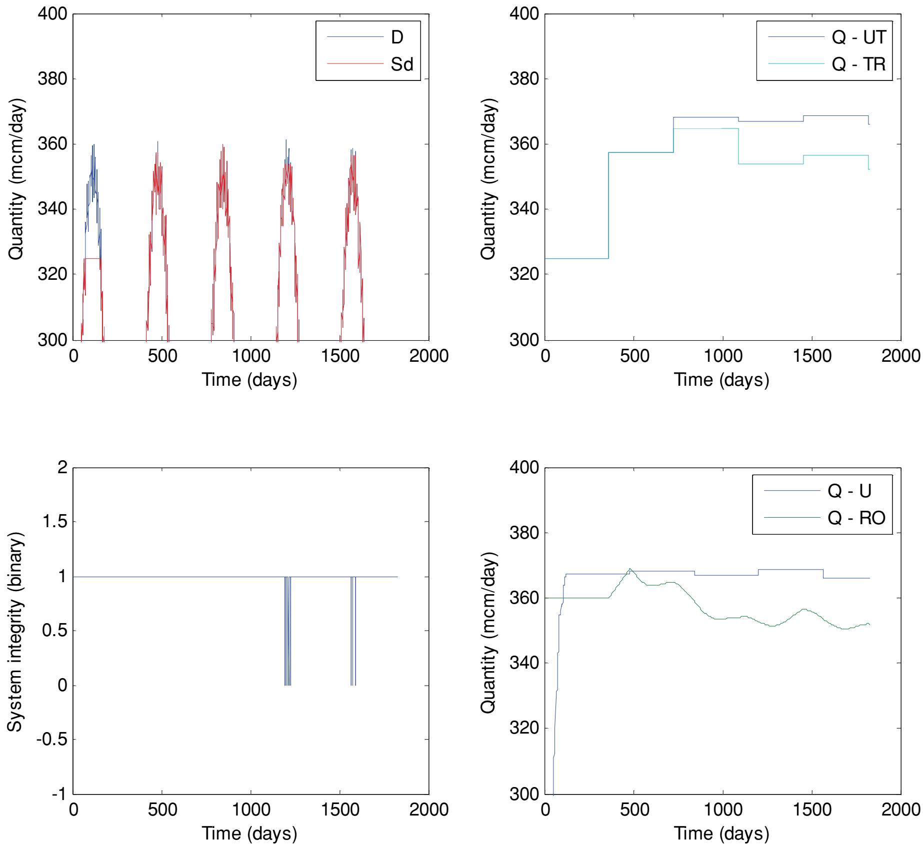


Figure 5.11: Imbalances between supply and demand due to imperfect information.

Average end-user price	=	179.6 kE/mcm
Quantity condition not met	=	86 out of 1825 days
Physical condition not met	=	11 out of 1825 days
Price condition not met	=	0 out of 1825 days

When the model used in this section is compared to the model described in Section 5.1, two conclusions can be drawn. First, the introduction of a trader produces the phenomenon of double marginalization and therefore causes an increase in end-user price. Second, coordination between supply and demand is more difficult, because there are now three individual decision makers instead of two, each with imperfect information about the others.

Coordination can be restored by replacing a contract agent with an integration agent. The functions of trader and resource operator are often combined in a single company, which can be modeled by using an integration agent. The new agent network is shown in Figure 5.12. This model is called Gasnet3. The reduced dataset is provided in Appendix II.

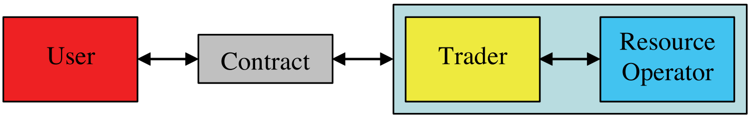


Figure 5.12: Gasnet3, a natural gas market model with an integrated trader and resource operator.

Figure 5.13A is another Simulink screenshot. It shows how the integration agent (shown in brown) is a subsystem on an equal footing with the user agent and the contract agent. Figure 5.13B shows how the integration subsystem consists of four further subsystems, two of which are actor agents: a trader agent and a resource operator agent. The other two are the financial subsystem and the contracting subsystem. The integrated company has a single money stock, which is determined in the financial subsystem. The seller offer for the supply contract is determined in the contracting subsystem, based on the information received from both actor agents. In this case, it is identical to the original resource operator's contracting algorithm.

The agent network described here is functionally almost the same as the agent network detailed in Section 5.1, because the trader's additional functionality (source selection and spot trading) is not used. The only addition is the trader's fixed costs. Therefore, the results are also virtually the same and will not be repeated here.

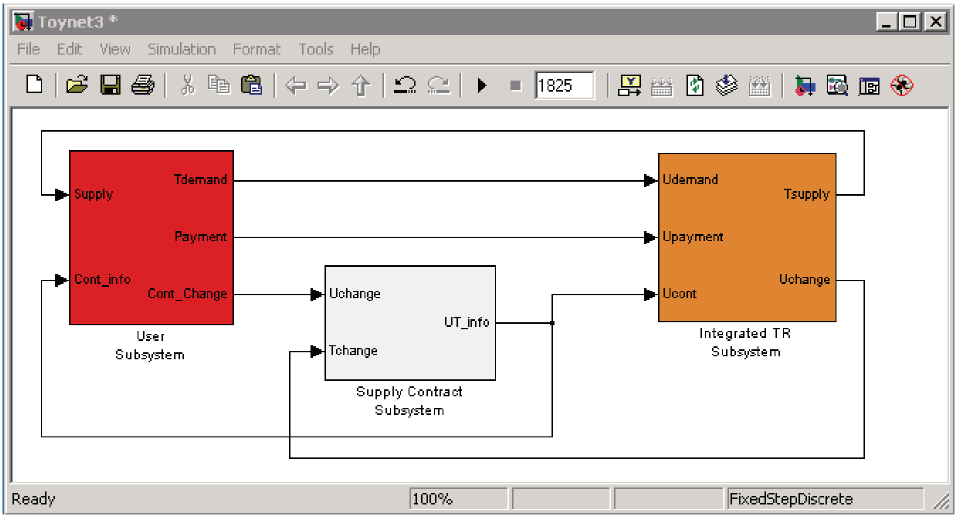


Figure 5.13A: Screenshot of a natural gas market model with an integration agent (top) and the contents of the integration subsystem (bottom).

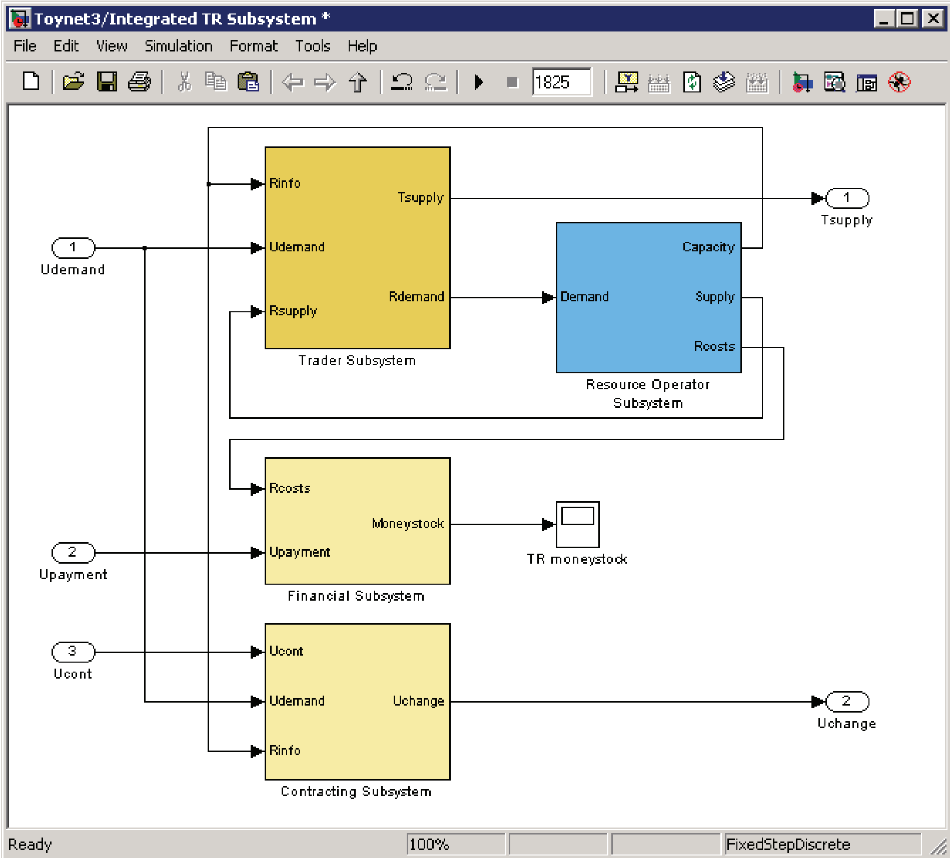


Figure 5.13B: Screenshot of the contents of the integration subsystem.

The final institutional agent to be included in the model is the spot market. Since, by definition, only traders are able to trade on the spot market, the agent network needs to be expanded a bit further. Combining Gasnet2 and Gasnet3, a new structure is created containing two traders, two resource operators and a spot market. Instead of including both users, a single user with two supply contracts is used. Figure 5.14 shows the resulting agent network, called Gasnet4.

This structure creates the possibility of studying some additional types of behavior. First, the user is able to switch between suppliers. This behavior is governed by the switching algorithm described by Eq. 4.5. Second, the traders now have access to the spot market as an additional source of supply. Their source selection algorithms determine the choice between gas from a resource operator and gas from the spot market. In this case, the traders use a reduced version of the preference scheme in Eq. 4.6, with three sources:

$$Spot_{low} > RO_{\max} > Spot_{high} \quad (5.2)$$

Third, the actual trade on the spot market is governed by the traders' spot trading algorithms. The numbers are given in Table 5.4. Two things are important to note. Trader 1 is integrated with a resource operator, so it uses the oil price as a reference for pricing. In addition, it offers its gas at a discount (20%) on the spot market. In contrast, trader 2 has a supply contract, so it uses the contract price as a reference for pricing. It offers its gas on the spot market at a premium (10%). Note also that a trader's base bid price is necessarily lower than its offer price.

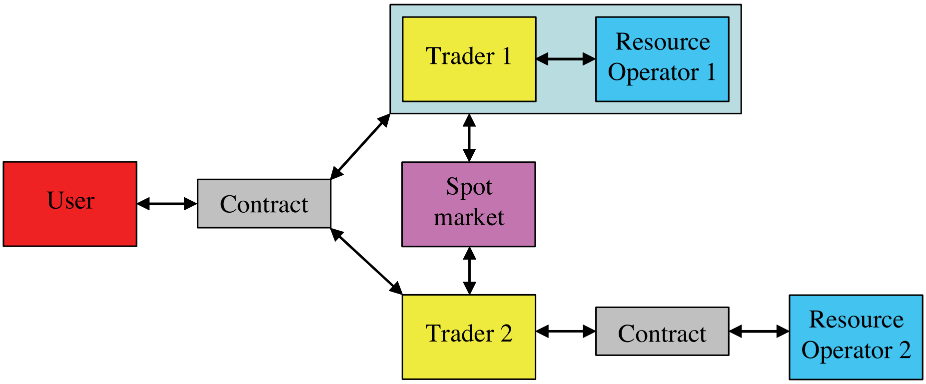


Figure 5.14: Gasnet4, a natural gas market model with multiple traders and a spot market.

Table 5.4: Data for the spot trading algorithm.

Variables	***Trader 1***	***Trader 2***
P - offer	0.8 * oil price	1.1 * contract price
Q - offer	R_{cap} - D_{user}	R_{cont} - D_{user}
P - base bid	0.75 * oil price	0.9 * contract price
Q - base bid	D_{user}	D_{user}
P - peak bid	1.2 * oil price	1.25 * contract price
Q - peak bid	D_{user} - R_{cap}	D_{user} - R_{cont}

Some more data have to be changed, because there are now two traders and two resource operators. Reservoir sizes are halved, contract quantities are halved, and each trader starts with a 50% market share. Finally, for the purpose of this example, two more adjustments are made. Only resource operator 2 invests in new fields and trader 2's strategy is changed. Until now, a trader's supply capacity has been limited by the size of its contracts with resource operators. However, in this market structure, a trader can also use the spot market as a supply source. It is assumed in this example that trader 2 wants to increase its market share and decides to rely on the spot market as a source for up to 20% of its gas (Tcsm = 1.25). For the complete dataset, see Appendix II.

Figure 5.15 contains some agent-level output from this model. The left hand graph shows the contract quantities changing from year to year. The user's switching algorithm dictates a shift to the cheapest supplier. In this case, the cheapest supplier is the integrated T-RO, because the integration agent prevents double marginalization. However, its production is in decline and therefore the amount it can supply decreases over time. Therefore, after an initial increase, its market share starts to decrease in year 3 and continues to do so. The T2R2-contract is at maximum capacity continuously. The right hand graph shows all players' money stocks. The R2 money stock is the only one which decreases significantly. This decrease is caused by trader 2's purchase of large amounts of gas on the spot market. R2's low sales revenues from the supply contract resulting from this do not cover its operational costs.

Figure 5.16 shows the system-level model output. The two left graphs show that supply does not match demand in the winters of year 4 and 5, causing a breach of system integrity. However, the bottom-right graph shows that this is not caused by a lack of supply contracts. Rather, it is trader 2 which cannot fulfill its contractual obligations. In other words, the physical condition has been violated. This is caused by a lack of coordination between the two traders. Each trader only has access to information about the production capacity of the resource operator it is linked to. Therefore, it does not know how much gas is available on the spot market and has to make an assumption. Its attitude to risk then determines what quantity above the amount it has contracted it will agree to sell to users. In this case, the risk taken was too high.

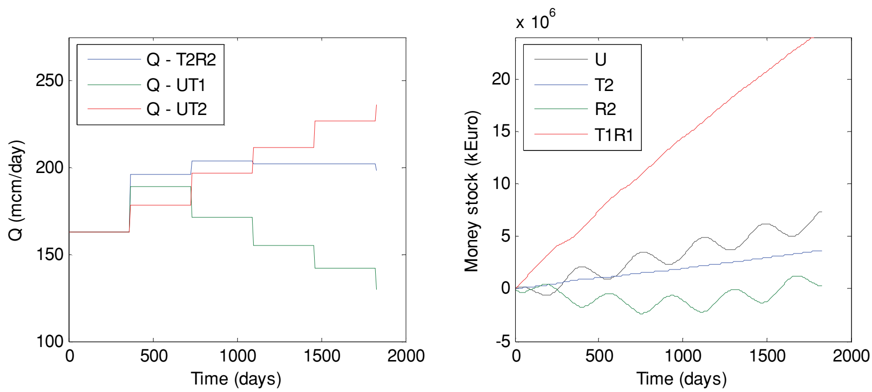


Figure 5.15: Agent-level output: supply contracts & money stocks.

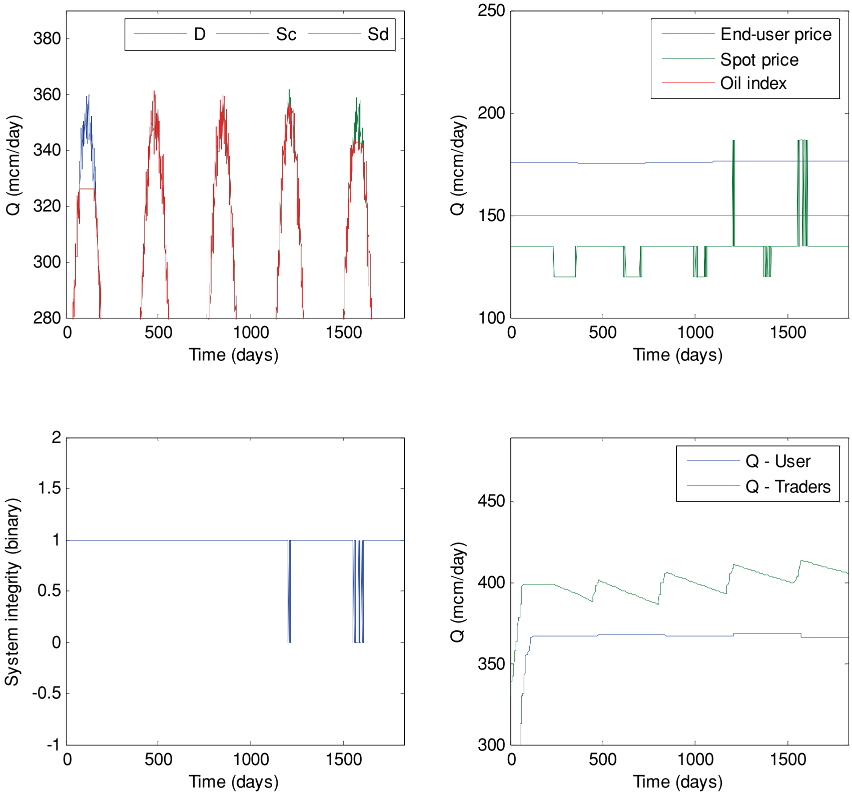


Figure 5.16: System-level output: affordability and supply security.

Average end-user price	=	175.7 kE/mcm (volatility: < 0.1 kE/mcm)
Average spot price	=	134.0 kE/mcm (volatility: 6.2 kE/mcm)
Quantity condition not met	=	197 out of 1825 days
Physical condition not met	=	46 out of 1825 days
Price condition not met	=	0 out of 1825 days

Finally, the top-right graph shows three prices. The oil price is still constant, while end-user price fluctuates slightly, because it is the weighted average of the prices charged by the two traders. When the cheaper trader gains market share, average end-user price goes down and vice versa. The spot price jumps between three market-clearing equilibria. In the 'low price' equilibrium, the offer quantity is larger than the base bid quantity (with peak bid quantity zero), so the market clears at the base bid price. In the 'medium price' equilibrium, the offer quantity is smaller than the base bid quantity (with peak bid quantity zero), so the market clears at the offer price. In the 'high price' equilibrium, the offer quantity is smaller than the peak bid quantity, so the market clears at the peak bid price.

These results translate into an average end-user price that is itself roughly the average of the average prices obtained in Sections 5.2 and 5.3, because the price formation processes taking place in the models described there are incorporated by the two traders in this model. The spot price is on average lower than the end-user price, but is more volatile. It should be noted that, in this model, the end-user price suffices as an indicator of affordability, because users are not affected by spot price developments. The quantity condition and physical condition are not met for a substantial number of days, as a consequence of the events described above.

Some additional empirical phenomena are reproduced by the models presented in this section. These are:

1. The limited amount of switching by end-users, allowing price differences to persist;
2. The co-existence of a spot market and longer term supply contracts.
3. The spot price's movement around the oil price, as documented by e.g. Asche et al. (2007);
4. Double marginalization, although this is a theoretical rather than an empirical phenomenon;

5.4 Introducing a network operator agent

Two more agents remain to be added to the agent network: the network operator and the storage operator. To limit complexity, they will be described separately. First, a network operator agent is added to the Gasnet2 model. The resulting model is called Gasnet5 and is shown in Figure 5.17. The network operator is linked to the trader through a transport contract and linked to the resource operator through a buffer contract. Again, a small expansion of the dataset is required, which is provided in Table 5.5. The complete dataset for this model is given in Appendix II.

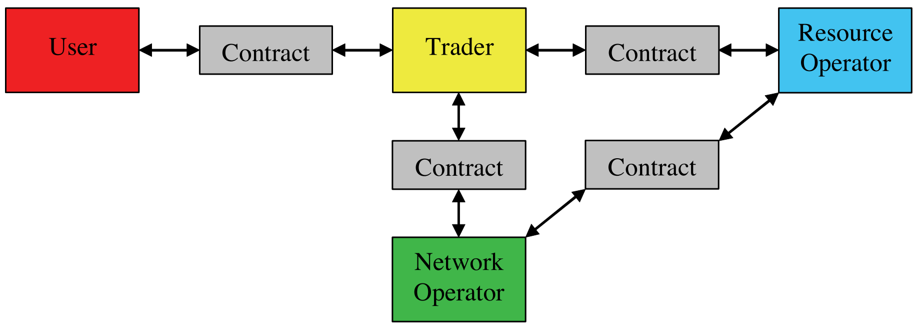


Figure 5.17: Gasnet5, a natural gas market model including a network operator.

Table 5.5: Network operator data.

Name	Description	Value
Initial money stock	-	0
Buffer margin	% of transport capacity covered by buffer	2%
Growth expectations	expected growth in demand for capacity	5%
Operational costs	Cost of operating the network	3 kE/mcm
Integrity costs	Cost of system integrity breach	10000 kEuro
Investment costs	Cost of investment	1500 kEuro/mcm
Lead time	Time to build new capacity	1 year
Sales margin	Margin made on asset base	5%
Transport capacity	Physical amount of capacity available	350 mcm/day
Penalty price	Penalty of imbalance for traders	300 kEuro/mcm
Regulatory Asset Base	Value of assets	1500 kEuro/mcm
Buffer contract	Buffer capacity hired from RO, price	7 mcm, 150 kE, 15 kE
Transport contract	Capacity hired to trader, transport price	350 mcm, 4 kE/mcm

The network operator adds some important functionality to the model. First, it adds the variable "transport capacity", which functions as a constraint to the delivery of gas by traders (Figure 5.18, top-left). Second, the balancing of supply and demand is centralized inside the network, which means system integrity (the physical condition) is agent-level output of the network operator agent (bottom-left). In the case of unbalance, the trader that caused it is fined an amount proportional to the magnitude of the unbalance (top-right). At the same time, the unbalance is removed with the help of a buffer (bottom-right). This figure shows that system integrity is breached several times in year two, coinciding with the depletion of the buffer.

This breakdown is caused by an additional parameter change. Just as in the previous model, the trader can afford to take some risk with contracting. However, in this case, it is not the spot market but the network operator's buffer which functions as a back-up. If the trader does not use any contracting safety margin (Tcsm=1) in determining his contract with the resource operator, it can reduce costs and in case of emergency be bailed out by the network operator. Figure 5.19, bottom-left, shows the gap between the UT-contract and the TR-contract which results. The values for the TN-contract are identical to those for the TR-contract, so the line cannot be discerned in the graph. Other system-level output includes an increase in end-user price as compared to previous models (top-right), because of the transportation costs which are now included in the price. The other graphs show the by now familiar supply and demand development (top-left) and the desired contract quantities of user, trader and resource operator (bottom-right). The information contained in these graphs is again summarized by the performance indicators below.

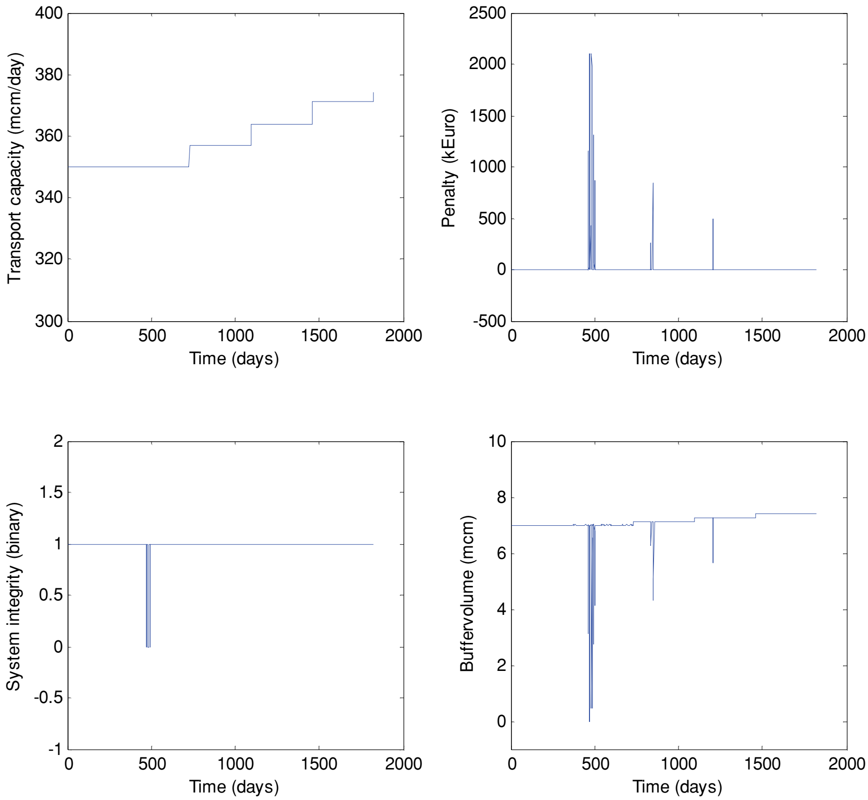


Figure 5.18: Agent-level output from the network operator.

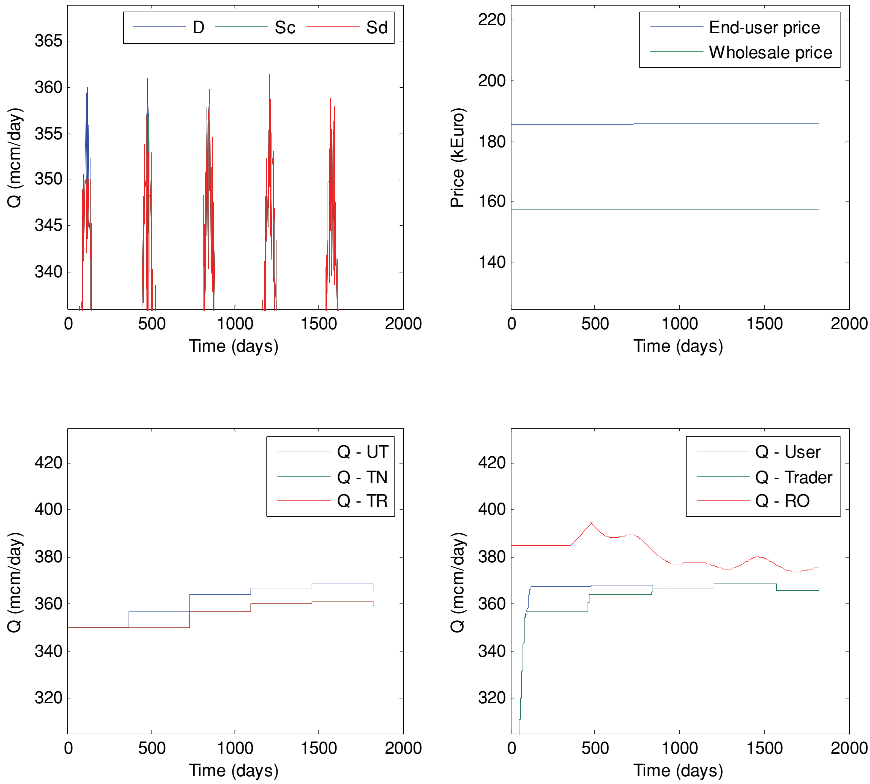


Figure 5.19: Affordability and supply security.

Average end user price	=	185.8 kE/mcm
Quantity condition not met	=	22 out of 1825 days
Physical condition not met	=	7 out of 1825 days
Price condition not met	=	0 out of 1825 days

This model shows the pivotal role of the network operator in securing supply. It captures the network operator's dual role of providing transport capacity and sustaining a buffer. It also makes apparent the importance of its relation to the trader, which has been radically changed by liberalization.

5.5 Introducing a storage operator agent

Finally, a storage operator can be added to the model. Again, Gasnet2 will be used as a basis. The storage operator is then integrated into the agent network by linking it to the trader through a storage contract. The resulting agent network is called Gasnet6 and is shown in Figure 5.20. The additional data required is provided in Table 5.6 and the resulting dataset is included in Appendix II.

In this example, it is assumed that the production capacity available from the resource operator is limited. Therefore, the trader needs a storage facility to be able to match the user's peak demand. This type of storage use is also called 'peak shaving'. As noted earlier, the renegotiation moment of the storage contract is halfway the gas year. This allows newly acquired storage capacity to be filled before the peak season (the first half of the gas year) arrives. The trader decides how much storage bundles to buy on the basis of the difference between its supply obligation to the user and the production capacity available from the resource operator.

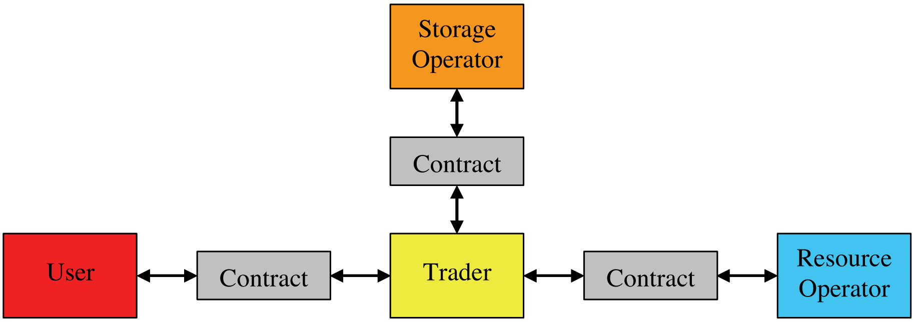


Figure 5.20: Gasnet6, a gas market model including a storage operator.

Table 5.6: Storage operator data.

Name	Description	Value
Smoneyinit	Storage operator's initial money stock	0 E
Sbpers	# Bundles per storage facility	5
Sbundle	Bundle size (production capacity, injection capacity, storage capacity)	7 mcm/d, 1 mcm/d, 200 mcm
Scosts	Operational costs	200 kE/day
Sinvcosts	Investment costs	150000 kE
Sgrexp	Growth expectations	1
Slead	Lead time	5 years
Smargin	Sales margin	1.15
Sthresh	Investment threshold	60 % sold
TScsm	Trader's storage contracting safety margin	0.1
TS	Initial contract (bundles, price)	3 bundles, 46 kE/bundle
Sres1	Working volume, Cushion volume, Initial pressure, Injection pressure, Well flow pressure, Reservoir temperature, Productivity index, Injectivity index, Installed production capacity, Installed injection capacity.	1000 mcm, 6000 mcm, $2.2*10^7$ Pa, $3.2*10^7$ Pa, $1.1*10^7$ Pa, 313 K, $2.3*10^{-8}$, $3*10^{-9}$, 35 mcm/d, 5 mcm/d

Figure 5.21 provides some agent-level output from the storage operator agent. The left hand graph shows production capacity, injection capacity and storage capacity as a function of the number of bundles contracted, which can be seen to increase from the initial three to four and then to five. The actual volume stored is also plotted. It decreases with production and increases with injection, with the contracted storage capacity as a maximum. The right hand graph shows production and injection over time. Production follows demand, because it is equal to the difference between user demand and supply from the resource operator. Injection is almost constant, because it is equal to injection capacity most of the time. However, this hinges on the condition of a sufficient surplus of resource operator production capacity.

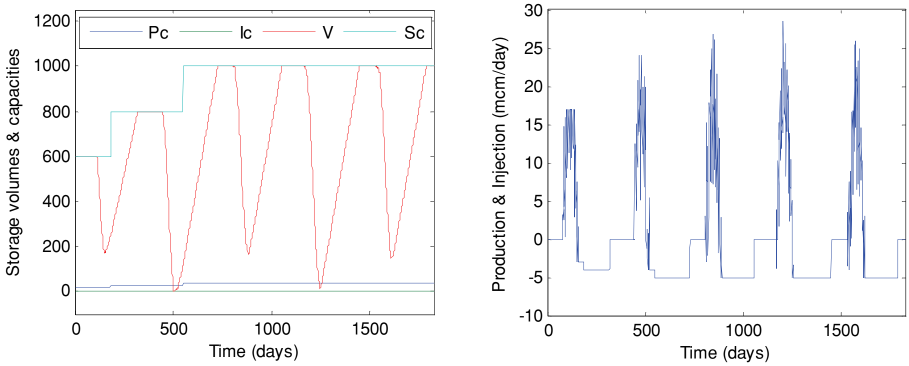


Figure 5.21: Agent-level output from the storage operator agent.

Figure 5.22 shows the processed output. End-user price fluctuates slightly, because the trader incorporates its storage costs in the capacity price. In this scenario, storage costs are slightly below the resource operator's capacity charge, which means capacity costs decrease as the storage provides an increasing share of capacity. This also means that average end-user price is slightly lower than in Gasnet2. System integrity is breached nine times, because in year 2 the storage is emptied before the peak season is over (see Figure 5.21). This happens because in this example the trader's contracting algorithm was based solely on production capacity, not on storage capacity. The quantity condition (bottom-right) is initially unfulfilled, but as the trader increases its number of storage bundles, it is able to provide more capacity and the two lines converge.

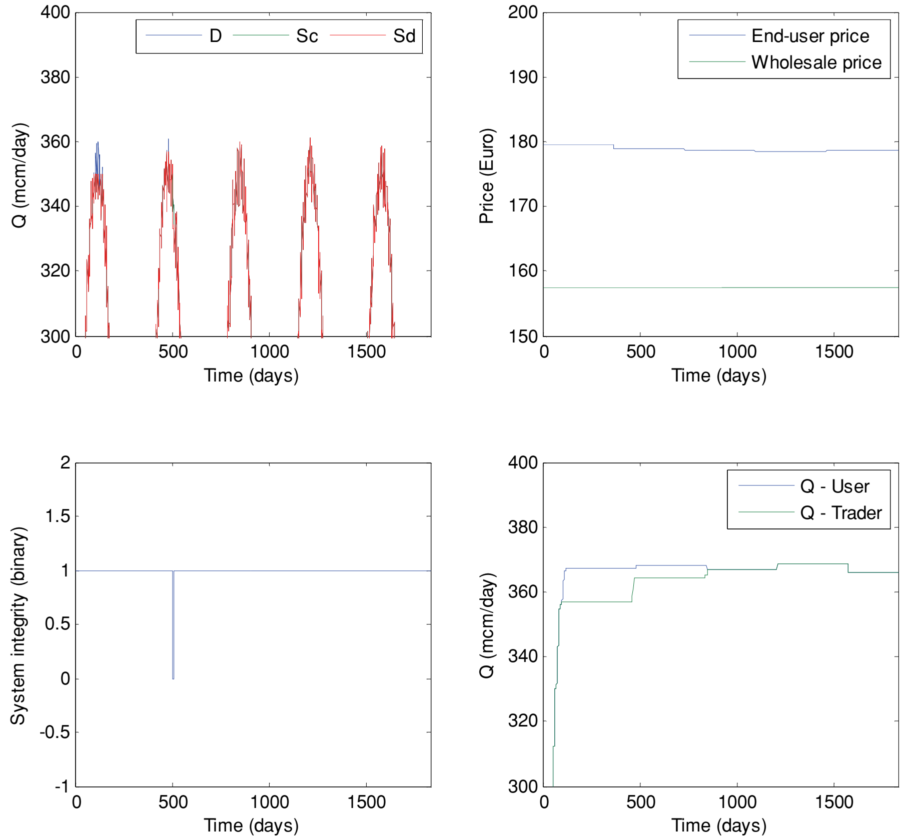


Figure 5.22: Affordability and supply security.

Average end user price	=	178.9 kE/mcm
Quantity condition not met	=	22 out of 1825 days
Physical condition not met	=	9 out of 1825 days
Price condition not met	=	0 out of 1825 days

A second example can be provided in which the storage is not used as a peak shaver, but as a volume shifter. This requires just two changes. First, the size of the storage is increased (although this is not strictly necessary). The adjusted dataset is given in Appendix II under the name "Gasnet6b". Second, the trader's source selection algorithm is adjusted. In the production season, the storage facility has a higher priority than the resource operator, which means the resource operator is still the 'swing supplier'. The difference between the two examples is highlighted in Figure 5.23.

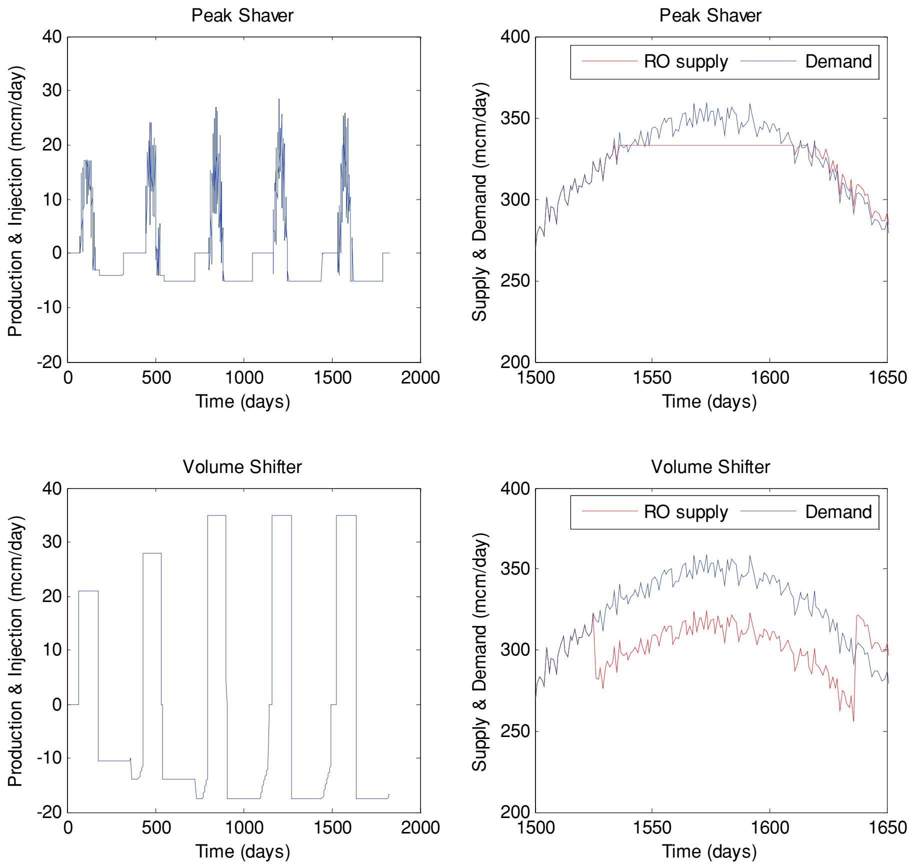


Figure 5.23: Peak shaving versus volume shifting.

The upper two graphs contain results from the peak shaver example, and the lower two contain the same variables from the volume shifter example. A comparison shows that peak shaver production is in general lower, has a shorter duration, and is more variable than volume shifter production. The opposite is true for the resource operator's production, which is complementary to the storage production profile. In the last part of both supply and demand graphs RO supply is higher than demand, because some of the gas produced is injected into the storage.

This example clearly shows the crucial function of storage when production is inadequate or inflexible. The approach followed here means that the way storage is used, is determined by the trader's source selection algorithm, within the technical constraints dictated by the storage facility. In principle, any combination of peak shaving and volume shifting behavior can be implemented.

5.6 A full value chain model for educational gaming

The final model presented in this Chapter is a model containing all agents from the library. Basically, it is a combination of Gasnet4, Gasnet5, and Gasnet6 with some adjustments. The starting point is the agent network from Gasnet4. Then, some adjustments are made. First of all, the integrated trader-resource operator no longer supplies users directly, but sells its gas on the spot market instead. Second, an extra trader is added to the model, which operates in the same way as the original trader. This means competition for supplying the user is retained. Third, the storage operator and network operator are added to the model and offer their services to all traders. The resulting agent network is called Gasnet7 and is shown in Figure 5.24.

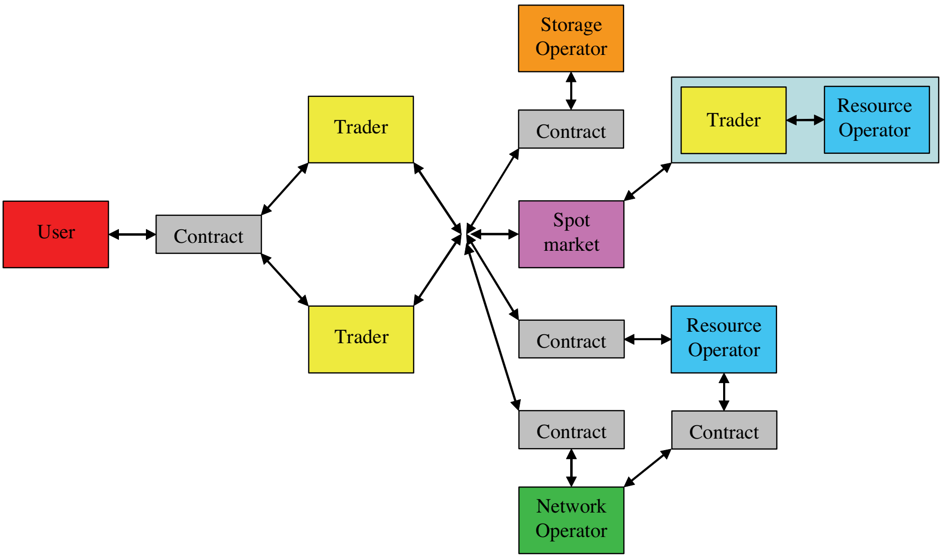


Figure 5.24: Gasnet7, an agent network containing all agents in the ENETSIM library.

This network is the first in this chapter to cover the whole value chain, and therefore also the first to potentially satisfy the minimal requirements identified in Section 3.4. Whether a model based on this network actually fulfils those requirements depends on the details of the market under study. This model, however, was not developed to represent an actual market in detail, but to be used in a game for educational purposes, a relatively new but promising application of economic models (Grevers and Van der Veen, 2008). The structure was chosen on the grounds that it incorporates the full value chain, including competition between agents in the production and trade segments, while keeping the overall model as simple as possible.

Changing the simulation model into a game was achieved by means of one fairly simple procedure, which was to change some of the endogenous decision algorithms into exogenous decisions made by the players. The game was designed for four (teams of) players:

- One trader, deciding on its spot trading strategy, its pricing strategy with regard to user contracts, and its purchase of storage capacity;
- One storage operator, deciding on its pricing strategy for its existing storage facilities and its investment in new facilities;
- One network operator, deciding on its investment in additional transport capacity and the amount of buffer capacity it contracts;
- And one integrated trader-resource operator, deciding on its exploration activity and its spot selling strategy.

Each team was then provided with the same, limited amount of information as the agent representing them, consisting of some public information available to all players and some private information available only to them. The handouts designed for each of the players are included in Appendix III. When the players had made their decisions, these could be added as input to the model, after which the simulation was performed as normal.

In the scenario created, each player's decision space incorporates a tradeoff. The trader has to strike a balance between setting high margins and obtaining a high market share. The storage operator must weigh the prospect of higher sales against the risk of stranded assets. The network operator is limited in its profitability by its duty to balance supply and demand. And finally, the trader-resource operator must try to optimize its sales volume with regard to the price on the spot market.

In addition, all players are faced with a coordination problem. The trader faces the risk of a price war with the other trader. The demand for storage depends on the liquidity of the spot market. The network operator's need for buffer capacity depends on the behavior of both traders. And the trader-resource operator's optimal production depends on the behavior of the other resource operator.

This setup can lead to very different results, depending on the choices players make. An example is given for the trader-resource operator's exploration decision. His exploration effort can be chosen in the range from 0 to 7.5 mcm/day of annually added production capacity. Three scenarios are defined for this choice: a high activity scenario (pc = 7.5) a medium activity scenario (pc = 5), and a low activity scenario (pc = 2.5). Figure 5.25 shows the agent's production profile (left graph) and its money stock (right graph). It can be seen that production starts to diverge rapidly in the second year of the simulation, when new fields start coming online. Near the end of the simulation, production in the high scenario is roughly double the production in the low scenario. The agent's money stock, on the other hand, shows a rather different picture. While money stocks diverge initially, they converge again in the second half of the simulation, with the medium scenario ending slightly higher than the other two. This is caused by the inverse relation between price and quantity on the spot market. The relative profitability changes over time because of the initial costs made for exploration, which repay themselves in later years in the form of additional production.

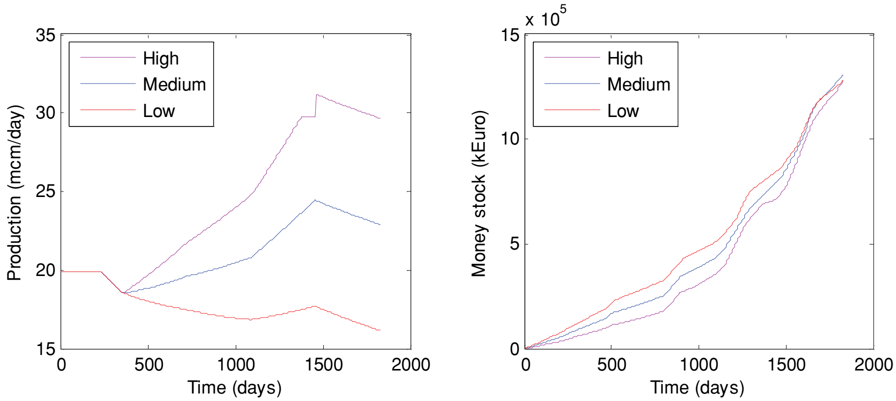


Figure 5.25: Production (left) and profits (right) for three levels of exploration activity.

Figure 5.26 shows the development of spot prices as a function of the agent's exploration decisions. The oil index was kept relatively constant, and the spot price can be seen to move around it. In the first half of the simulation, spot prices are almost the same for each scenario. In the second half, prices start to diverge. In the "medium" scenario, spot prices are below the oil index for most of the year, with peaks of increasing length occurring during winter. In the "low" scenario, peaks are higher and longer in an earlier stadium. In contrast, peaks in the "high" scenario become shorter and prices fall to a low level in the summers of year four and five.

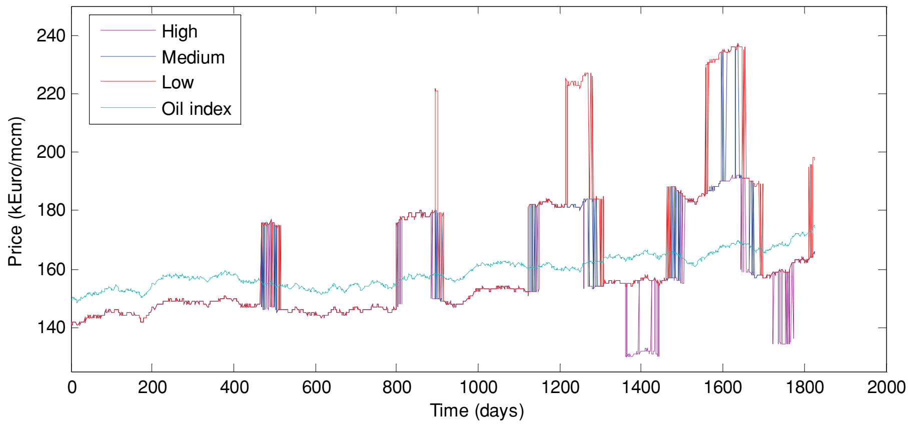


Figure 5.26: Gas prices for three levels of exploration activity.

This gaming exercise not only served an educational purpose, but the feedback on the model obtained from the participants was also used to improve the model. The gaming exercise is therefore also a good example of iterative participatory modeling, as described in Section 4.7. Until now, the players of the game have been students. The iterative participatory modeling principle can be utilized to its maximum when industry stakeholders are involved by allowing them to play the role of the agents representing them and evaluating the model in the light of their own experience. In the long term, this can provide ENETSIM with a degree of validity unattainable by other means.

5.7 Conclusions regarding the ENETSIM framework

In the previous sections, some applications of the ENETSIM framework have been presented. It has been shown that the framework can be used fruitfully to develop models which can determine the affordability and supply security associated with a given market structure. The approach outlined in Chapter 3 has been to start with a simple model containing most market imperfections and then gradually increasing granularity and scope. This culminated in a model fulfilling the minimum requirements set out in Chapter 3. Looking at the similarities rather than the differences between the models used in this chapter, some preliminary conclusions can be drawn.

The first conclusion is that the ENETSIM framework enables the representation of supply insecurity due to its incorporation of several market imperfections. The choice for a dynamic system approach enables the representation of supply and demand mismatches in the four submarkets modeled (retail, wholesale, transport and storage). However, it does not necessarily yield out-of-equilibrium outcomes. Given the dynamic setting, model outcomes are a function of the agent network, agent behavior, and the data.

Starting with the agent network, the main innovation is the removal of an overarching market equilibrium in favor of a set of governance structures. In such a setting, the issue of coordination between consecutive parts of the value chain arises. In the case of integration, coordination is 'perfect' because there is a single decision maker controlling both activities. In the case of a contract, coordination is less than perfect, because there is an incomplete exchange of information between agents. In the case of a market, coordination is the worst, because there is virtually no information exchange. This phenomenon is most pronounced in the investment decisions of agents, where integration provides certainty about the future utilization of infrastructure as opposed to a market, where agents tend to under-invest to reduce risks.

With regard to agent behavior, the main enabler of actual out-of-equilibrium situations is the move from substantive to procedural rationality. While in certain situations both types of rationality produce identical results, the phenomena of imperfect information and imperfect foresight (i.e. uncertainty) cause results to diverge. The main sources of imperfect information are the confidentiality of other agents' strategies and of their physical assets. The main sources of imperfect foresight are future developments in demand, market share, and other agents' investment behavior. This lack of knowledge requires agents to make assumptions about such matters which may be incorrect. When they are, the market is out-of-equilibrium. The acknowledgement that assumptions and expectations are possibly incorrect in turn drives agents towards risk averse behavior, necessitating the representation of such motives in the model.

The data have played a minor role in this chapter, but are crucial in the assessment of actual gas markets. ENETSIM models are highly non-linear, because of a number of thresholds which, once exceeded, cause an abrupt change in model output. The main threshold phenomena are the system integrity variable switching from one to zero, the decision whether or not to undertake a large investment (e.g. in a storage facility) and the volatility of the spot price as a function of the set of bids and offers. When the system is near a threshold, a small change in the data can have a large impact on model output.

The second conclusion is that the simultaneous representation of affordability and supply security enables an analysis of the tradeoffs between them. First of all, the comparative advantage of integration with regard to coordination can be offset by a second issue, competition. Whereas coordination is perfect between integrated agents, this coordination creates a disadvantage to other agents active in the same part of the value chain if one of the integrated agents has a monopoly. The integrated agent can be favored unfairly at the cost of non-integrated ones. The contract has an intermediate position, with new entrants being put at a disadvantage for the duration of a contract between established players. Therefore, the issues of coordination and competition together produce a tradeoff between affordability and supply security.

A related tradeoff exists between flexibility and stability. In case of a market, agents have the maximum amount of freedom to change buying/selling prices and quantities. This has the positive effect of allowing prices and quantities to adjust quickly and adapt to the new market situation. However, risk aversion often makes consumers and suppliers prefer price stability and security of supply or security of demand respectively. Such certainty is best provided by contracts and integration. Tradeoffs between affordability and security can also be found on the level of individual agents. On the buyer side of each submarket, a higher risk tolerance translates into greater affordability, but lower security. On the seller side, a higher risk tolerance means profits are potentially higher but also more uncertain.

Finally, it has been shown that the ENETSIM framework is of sufficient generality to generate a large number of different models and address a wide range of phenomena. While this invites the criticism that it provides the modeler with too many degrees of freedom, this can be a strength rather than a weakness. As almost any type of behavior can in principle be implemented, the choice for a certain agent network, decision algorithm or data point can be based on direct empirical observation or on feedback obtained through iterative participatory modeling. Ultimately, this can lead to a degree of input validity not attainable by models which have to select input on the basis of computability.

6. The liberalization of the Dutch natural gas market

6.1 Structure of the Dutch market study

In the previous chapter, some general ENETSIM models were developed to showcase the possibilities and consequences of the ENETSIM methodology. In this chapter, the methodology will be used for studying the natural gas market of a specific country. The Netherlands was chosen as the subject of this study for reasons of familiarity and data availability. However, it is also a country especially suited to a case study, as it has a unique combination of characteristics the study of which is also relevant to many other EU countries. Among the most important of these characteristics are its function as a transit country, its developing spot market, its extensive resource base which is in decline, its active regulatory authority and its two linked networks, transporting gas of different qualities.

The country study consists of two parts. In this chapter, the performance of the Dutch market under its pre-liberalization structure is compared with its performance under the post-liberalization structure. In the next chapter, the sensitivity of the post-liberalization structure's performance to different scenarios for the future of the Dutch natural gas market is analyzed. This means the study has both a prospective and a retrospective element. On the one hand, it serves as an evaluation of the liberalization process. On the other hand, given the fact that liberalization has taken place, it looks at the threats and opportunities on the road ahead.

Two ENETSIM models are constructed to perform this study: the GasnetNL1-model, which represents the Dutch market before liberalization, and the GasnetNL2-model, which represents the market after liberalization. Initially, both models are provided with a more or less identical dataset. This means differences in model outcomes can be attributed solely to the shape of the agent network and the agents' decision algorithms. It should be noted, however, that the dataset associated with the GasnetNL1-model necessarily differs somewhat from those in GasnetNL2, because of the different shapes of the agent networks. In the second part of the study, scenario analyses are performed which serve the dual purpose of ascertaining the GasnetNL2-model's sensitivity to parameter changes as well as the Dutch gas market's robustness to uncertain future developments. The structure of the country study is summarized in Figure 6.1.

The performance of each model is analyzed with regard to security and affordability in the same manner as the models presented in the previous chapter. In addition, the merit of different policies and market structures is analyzed by assessing the comparative performance of different models. With regard to supply security, the study focuses on risks internal to the economic system. This means the external risks identified in Section 2.6 (weather, facility and political risk) will not be analyzed. A simulation period of twenty years is chosen, so that short term risk and long term risk can both be analyzed.

The remainder of this chapter is structured as follows. Section 6.2 provides the context of the study by presenting a short history of natural gas in the Netherlands. This policy overview is based largely on De Jong et al. (2005), which provides a more extensive description of Dutch energy policy. Section 6.3 describes the pre-liberalization structure of the Dutch market and the GasnetNL1-model based on it. The results obtained from this model are presented in Section 6.4. Next, the post-liberalization market structure is described along with the GasnetNL2-model in Section 6.5. In Section 6.6, the results for the GasnetNL2-model are shown. In Section 6.7, some conclusions regarding the effects of liberalization are drawn.

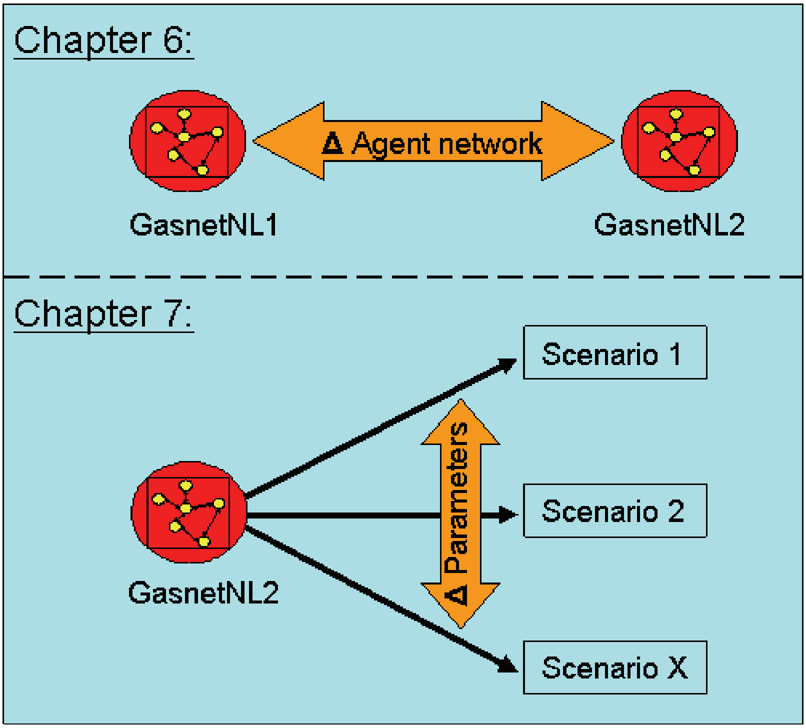


Figure 6.1: The structure of the Dutch market study. In Chapter 6, the performance of two different agent networks is compared. In Chapter 7, a single agent network is subjected to different scenarios.

6.2 The evolution of the Dutch natural gas market and Dutch energy policy

The Dutch natural gas industry started to take shape after the discovery of the Groningen field in 1959. The government became a business partner of Shell and Exxon and co-founded both Gasunie and the Maatschap Groningen. Gasunie's task was to buy natural gas from producers, transport it and then sell it to consumers. In addition, regional distribution companies were established with provinces and municipalities as their shareholders. These fulfilled a similar function, but on a smaller scale. The main exploration and production company at this time was the NAM, which was a joint venture of Shell and Exxon. At this time, the government's strategy was to maximize income from the natural gas it owned by creating an industry structure that allowed the government to take the lion's share of the profits and creating as large a customer base as possible. It was widely believed that there was only a limited time span for natural gas to be used, as nuclear energy was destined to take over as the major source of energy. Therefore, production was to be maximized. As there was no structural energy policy at this time, natural gas policy was mainly developed from a producer perspective.

In the seventies, the government started to change its strategy. Under the influence of the oil crisis and the lack of progress in nuclear energy research, natural gas was now perceived as a valuable, scarce resource that should be used sparingly. The new strategy had two focal points. The first was to make sure that as much natural gas as possible would be retrieved from the Dutch subsurface. To this end, the small fields policy was designed, which entailed a guarantee to all independent producers that they could sell their gas to Gasunie at a high load factor (i.e. continuous production at or near full capacity) at oil-linked prices. The second was to preserve natural gas where possible, which meant limiting the use of natural gas to its most profitable applications. This second goal was implemented by placing a cap on domestic production. In this period, a coherent energy policy was formulated explicitly for the first time. The content of this policy fits well within the affordability-security-sustainability framework outlined in Chapter 1. It should be noted that, at this time, security of supply was the principal policy aim, low prices were of secondary importance and sustainability was mentioned only as an afterthought. The adoption of this framework created a structural tension in Dutch natural gas policy. The government wanted to keep energy prices low on behalf of consumers, but also wanted to keep natural gas prices high to maximize its revenue from natural gas production.

In the eighties, attention started to shift from the security of energy supply to sustainability. Two major events caused this shift. The Chernobyl nuclear disaster made the use of nuclear energy highly problematic. The UN Brundtland-report warned of the global warming, pollution and acidification caused by large scale energy use. This shift did not affect natural gas policy very much, although it did cause some societal resistance to new natural gas projects. The underground storage facility planned near Langelo and the commencement of production from fields in the Waddenzee were both contested. Eventually, the underground storage facility was built as planned, but production from the Waddenzee was delayed for more than twenty years.

In the nineties, a new and radical change in policy started to form. The EU's decision to apply the internal market principle to energy markets combined with domestic dissatisfaction with the electricity industry, made the government decide to liberalize its natural gas and electricity markets. For natural gas, this was mainly done to comply with European directives as the government was satisfied with the status quo. Therefore, its initial strategy was to do no more than the minimum required. Over time, however, the belief that liberalization would be good for affordability gained ground, and eventually the Dutch natural gas market was reformed quite extensively, especially when compared to the rest of the EU. The current market structure approaches the post-liberalization structure outlined in Section 2.3. The most notable differences are the continued (partial) public ownership of several large companies, and the continuation of both the small fields policy and the cap on domestic production.

1999 saw the first edition of the Ministry of Economic Affairs' Energy Report, later editions of which were to appear every three years. The 1999 report (Ministerie van Economische Zaken, 1999) was structured along the lines of the three energy policy goals, with affordability and sustainability receiving the most attention. Security was deemed to be 'under control'. Affordability was to be enhanced by speeding up the liberalization process and sustainability was to be increased by promoting energy conservation and a transition to the use of renewable energy sources. From this moment on, the government positioned itself as a body governing the market, providing it with the right boundary conditions to fulfill society's objectives, rather than participating in the market itself (cf. Section 1.2). At this point, affordability also started to be used interchangeably with economic efficiency.

In the 21st century, the emphasis of the Energy Reports started to change. The government set itself a new overarching target: to guide the transition to a sustainable energy system. The choice for this objective implied no specific target for the natural gas industry, although natural gas was described as an important transition fuel that could bridge the time before sustainable fuels would take over completely. In the 2002 Energy Report (Ministerie van Economische Zaken, 2002), this target was treated as a fourth subject alongside the traditional three. In addition, security was once again high on the agenda, due to the California crisis and Europe's increasing import dependency. This trend continued in the 2005 Energy Report (Ministerie van Economische Zaken, 2005), which focused explicitly on "two major, mainly international challenges: ensuring supply security and tackling the global climate problem". According to this report, the market should take care of affordability, whereas security and sustainability are external effects which require government intervention (p.23). The transition to a sustainable energy system was again identified as the government's main long term goal, and started to take on a different meaning. No longer a means to fulfilling the sustainability goal, it now included security and economic efficiency as well (p. 29).

In its most recent policy document, the Energy Report 2008 (Ministerie van Economische Zaken, 2008), the government starts by reiterating its vision of the transition to a sustainable energy system, which now seems to have lost its original meaning and is instead described as a cleaner, smarter, and more varied way to supply energy. The main body of the document focuses on three subjects: access to energy sources, energy use in the Netherlands and energy infrastructures. Although it remains unclear why the government now partitions energy policy into these categories, the actual policies following from this partition are familiar. First of all, the government still provides rules and regulation to steer markets in the right direction, which is alternately called improving the functioning of markets, improving the investment climate, and improving the regulatory framework. Second, energy conservation and the use of renewable energy sources are still used to protect the environment. Third, maintaining good relationships with producing countries and diversifying supply sources are still used to secure supply. The main novelty of this document lies in the government's stated ambition to actively pursue innovation in infrastructure technology.

With regard to natural gas policy, the main point of interest is the government's plan to turn the Netherlands into a "gas roundabout". As the Netherlands' dominant upstream position is in decline, the plan is to establish a prominent midstream position instead. Such a position would entail attracting gas from many different places through the availability of transport infrastructure, underground storages, LNG import terminals and liquid gas exchanges. This is made possible by the Netherlands' geographically favorable location, its still sizable production, its favorable geological conditions and its know-how with regard to natural gas.

Summarizing, Dutch natural gas policy started out as the maximization of government revenue from its natural gas resources. Subsequently, it became a part of energy policy in general and focused on using natural gas as a tool to make the supply of Dutch energy affordable, secure and sustainable. Liberalization did not change the goals of policy, but it did radically change the government's method of achieving them. Currently, the goal of energy policy is to guide the transition to a sustainable energy system, whereas the goal of natural gas policy is to create a gas roundabout, which in turn is hoped to increase affordability and security.

Dutch natural gas policy is relevant to this study in a number of ways. First, the current regulatory environment is incorporated in the models developed for the analysis. Second, the scenarios used in the study are based on the future development of both the natural gas market and other energy markets as envisioned in the government's Energy Reports. Third, the results of the study can be used to ascertain whether current policy achieves its aims and whether different policies would improve or worsen the performance of the natural gas market.

6.3 The pre-liberalization model: GasnetNL1

6.3.1 The agent network

The first step in constructing the pre-liberalization model is to choose an agent network which corresponds to the Dutch pre-liberalization market structure. Where feasible, the companies active on the Dutch gas market before liberalization are modeled on a one to one basis. However, a number of simplifications have been made to keep the model tractable and understandable. In accordance with the model requirements outlined in Section 3.4, some actor agents of the same type are aggregated into a single actor agent, and technical detail is limited, so the model has a rather course granularity. Users are grouped into six categories, mainly so the effects on different user groups can be isolated. Storage operators are aggregated into a single operator, which is part of the NAM. Independent resource operators active in the Netherlands (except from the NAM) are also aggregated into a single operator. Finally, all local distribution companies (which are integrated trader-network operator companies) are aggregated into a single company.

As the model describes the Dutch market, the boundary between the system and its environment is drawn at the Dutch border, with three notable exceptions:

1) Foreign resource operators which export gas to the Netherlands are included as a single resource operator called "Import".

2) Foreign consumers which receive their gas from the Netherlands are included as two user agents, called "H-gas export" and "G-gas export" respectively.

3) Storage facilities which are located across the border but are connected to the Dutch transport network are also included in the model.

In total, 14 actor agents and 7 institutional agents are included in the model, composing 11 independent firms. Six different types of consumer are included in the model: households, commercial, industry, power generation, H-gas export and G-gas export. Two traders and two network operators are included, combined into two integrated trader-network operator companies. One of these represents the Gasunie, the other represents the local distribution companies (LDC's), also known as utilities. One storage operator agent is included as part of an integrated resource operator-storage operator agent. This integrated entity represents the NAM. Two independent resource operators are included, one representing domestic producers ("small field operators") and another representing foreign producers ("import").

In addition to the three integration agents mentioned above, the model contains four contract agents. There are two supply contract agents in the model, one representing the LDC's supplies and one representing Gasunie's supplies. One production contract is included, representing Gasunie's purchases from foreign producers, independent domestic producers and the NAM. Finally, the model contains one storage contract, which represents Gasunie's rent of storage capacity from the NAM. The complete agent network is shown in Figure 6.2. A screenshot of the actual Simulink model is shown in Figure 6.3.

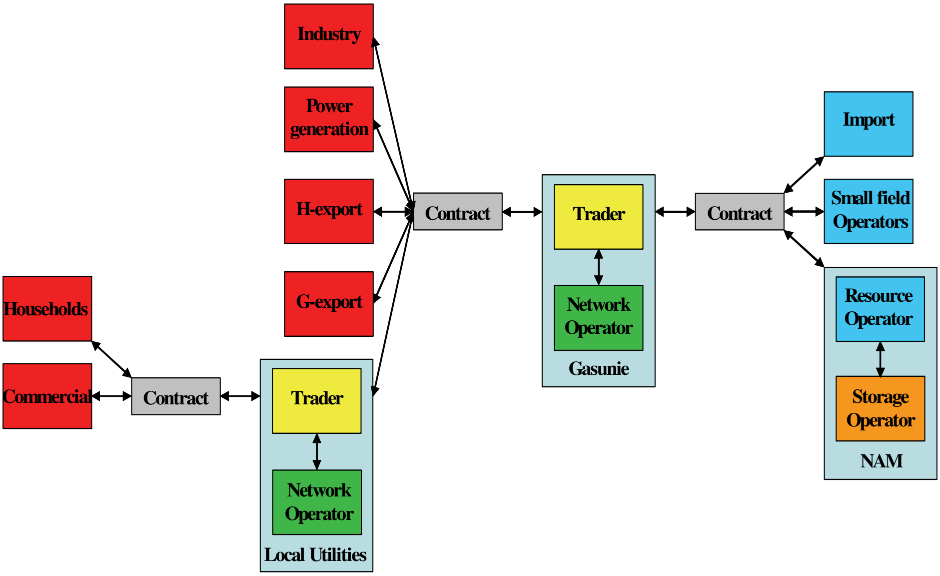


Figure 6.2: The GasnetNL1 agent network, representing the Dutch gas market before liberalization.

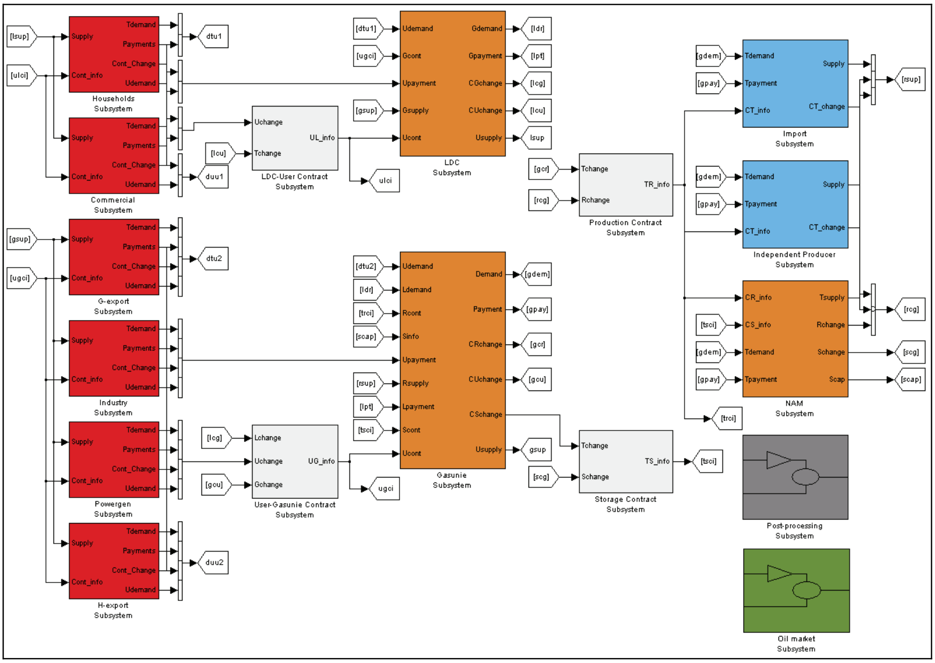


Figure 6.3: A screenshot of the actual GasnetNL1 model, representing the Dutch market before liberalization.

The next step in model construction is to specify the decision algorithms for all agents in the network. Each algorithm is described in detail in the following subsections.

6.3.2 Agent behavior

User agents have two decision algorithms: demand generation and contracting. All user agents in GasnetNL1 have identical algorithms, which means they differ only with regard to the data supplied to each agent.

The demand generation algorithm is equal to the algorithm specified in Eq. 4.5. It should be noted that users differ in one additional respect: the quality of the gas they consume. Households, Commercials and G-export consume G-gas, whereas Industry, Power generation and H-export consume H-gas. These two gas qualities are treated as two separate products, although one can be converted into the other (see the Gasunie agent).

The contracting algorithm normally consists of two parts: the maximum allowed quantity of gas contracted and the choice between suppliers. However, in the pre-liberalization model all users are supplied by monopolists. This means they cannot choose between suppliers and so the switching algorithm is not used. The maximum allowed quantity of gas demanded is a function of past demand, expectations of future demand and a safety margin, as described in Section 4.5.1.

The *local distribution company (LDC) agent* consists of a trader agent and a network operator agent, bound together by an integration agent. This means the LDC agent has four decision algorithms: the trader's source selection algorithm, the network operator's balancing and investment algorithms, and the integration agent's contracting algorithm.

Since the trader has only one supply source (Gasunie), the source selection algorithm simply passes user demand through to Gasunie, within the constraint that demand cannot exceed transport capacity.

The network operator's balancing algorithm compares user demand with trader supply and tries to eliminate any unbalance with the use of its buffer. Whether this is successful or not determines the network operator's system integrity.

The network operator's investment algorithm for building additional capacity is a function of past demand, expectations of future demand and a safety margin, as described in Section 4.5.5.

The integration agent's contracting algorithm determines the contract offer made to user agents and the contract request to Gasunie. The quantity offered to users is equal to their maximum past demand times a safety margin, and the quantity requested to Gasunie is equal to the quantity offered to users. The prices (commodity and capacity) in the Gasunie contract are determined by Gasunie. The commodity price in the user contract is determined by adding a markup to the LDC agent's commodity purchasing costs and the capacity price is determined by adding together the network operating costs and the capacity purchasing costs and then adding a markup.

The *Gasunie agent* is identical in structure to the LDC agent, but its decision algorithms are specified differently.

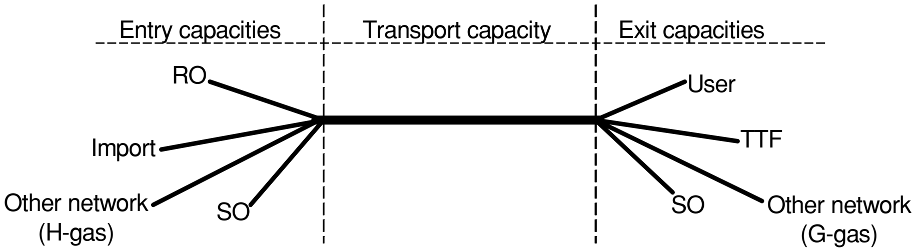
The trader's source selection algorithm is used to choose between four sources of supply: import, small field operators, the NAM and the independent storage operator. Flows from import and small field operators are held constant, as Gasunie purchases them without any added flexibility. It then tries to balance supply and demand by requesting the missing amount of supply from the NAM. If supply from the NAM is not adequate for balancing supply and demand, the storage operator functions as a supplier of last resort. An added complication is that the trader faces both demand for H-gas and for G-gas. Import and small field operators supply only H-gas, whereas the NAM and the storage operator can supply both. As the Gasunie trader agent can use the network operator's blending capacity, it converts any excess H-gas into G-gas and in so doing minimizes G-gas production.

The network operator's balancing algorithm compares user demand with trader supply in both the H-gas network and the G-gas network. Any unbalance is eliminated where possible with the help of the H-gas buffer and the G-gas buffer respectively. Whether this is successful or not determines the system integrity of each network.

The network operator's investment algorithm for building additional H-gas and G-gas capacity is a function of past demand, expectations of future demand and a safety margin, as described in Section 4.5.5. Its investment in blending capacity is determined by the difference between inflexible H-gas supply and minimum H-gas demand, as this determines the maximum amount of H-gas that has to be blended.

The integration agent's contracting algorithm determines the contract offer made to the user and LDC agents and the contract request to resource operators and the storage operator. The quantity offered to users and the LDC is equal to their maximum past demand times a safety margin. Gasunie has limited influence on the quantities contracted from resource operators. As part of the small field policy, Gasunie is obliged to buy all gas offered to it by domestic producers. For this reason, the small field operator and the NAM set the quantities in their respective contracts. Gasunie does choose a quantity for the import contract. The quantity chosen is equal to the average demand for H-gas minus the contracted supply from other sources, excluding storage. The prices (commodity and capacity) in the user and LDC contracts are determined by Gasunie. The commodity price in the user contract is determined by adding a markup to Gasunie's commodity purchasing costs and the capacity price is determined by adding together the network operating costs and the capacity purchasing costs and then adding a markup. The prices (commodity and capacity) in the production and storage contracts are determined by the resource operator and storage operator respectively. The quantities requested to the storage operator are equal to the expected peak demand minus the peak capacity available from resource operators.

The diagram below is a schematic representation of the Gasunie transport network.



The <u>bargaining algorithms</u> of the two *supply contract agents* (user-LDC and user/LDC-Gasunie) function exactly as described in Section 4.5.7. The selling party determines the commodity price, the capacity price and the maximum quantity available, after which the buying party chooses a quantity equal to or smaller than the maximum quantity. The duration of the supply contracts is one year.

The *storage operator agent* contains three decision algorithms: operation, investment and contracting.
Its <u>operation algorithm</u> functions largely as described in Section 4.5.4. The agent has the potential to operate H-gas storages as well as G-gas storages, which are included separately but treated in the same way.
The <u>contracting algorithm</u> is straightforward. The storage operator agent offers an amount of bundles for rent equal to the amount currently available plus the amount available after investing in one additional storage. The price is determined as a markup over operating costs.
The <u>investment algorithm</u> is based on the storage contract. If the amount of bundles sold at a distance in time equal to the lead time of building a storage is greater than the number of storages currently available, it invests in that number of storages which will close the gap.

The structure of the *storage contract agent* is modified somewhat. The number of variables in the storage contract is extended from two (price and quantity) to seven (price and six quantities). The quantity variables represent the different quantities contracted over time. As the lead time for building a storage is five years (in this model), the number of quantity variables included is six: one quantity for the current amount of storage, one quantity for a year ahead, etc. up until five years ahead. This provides the storage operator with reliable information about the future need for storage.
The <u>bargaining algorithm</u> works as normal, with the storage operator setting price and maximum quantity and Gasunie setting quantity equal to or below the maximum. This process determines the quantity five years ahead. The quantity five years ahead then becomes the quantity four years ahead, etc.

The *import agent* contains three decision algorithms: production, investment and contracting. However, the <u>investment algorithm</u> is not used, as modeling the investment process of foreign producers is beyond the scope of this model. Instead,

an initial estimate is made of the volumes available for export to the Netherlands. These volumes are then modeled as the reservoirs available for production.
The contracting algorithm offers all available production capacity for sale to Gasunie at the oil-indexed price level. No flexibility is offered, as production is assumed to be too remote from the Dutch market to adjust to daily demand fluctuations timely.
An amount of gas equal to the contracted amount is then produced daily in the production algorithm.

The *small field operator agent* has the same structure as the import agent. The main difference lies in the investment algorithm. This algorithm represents exploration in the Dutch subsurface. Its investment is equal to the minimum of two quantities: the number of prospects expected to be profitable at current prices, and the internal means for investment available. It is assumed only H-gas is discovered and produced.
The contracting algorithm sets the daily contract quantity equal to production capacity. Again, no flexibility is offered, but not for technical reasons. The small fields policy guarantees small field operators a constant, high load factor, which is reflected in the lack of flexibility in the contract.
Its production algorithm then sets daily production equal to production capacity for all producing reservoirs.

The *NAM agent* contains five decision algorithms: operation and investment in the storage operator agent, production and investment in the resource operator agent and contracting in the integration agent. Initially, the resource operator agent owns one G-gas producing field (Groningen) and one H-gas producing field (an aggregate of its small fields). Its investment algorithm is identical to the small field operator's algorithm, so only H-gas is added to its reserves.
Its production algorithm sets production equal to Gasunie demand. Gasunie demand consists of demand for H-gas and G-gas. Therefore, Gasunie sends information about available blending capacity to the NAM. This enables the NAM to maximize production from its small fields by producing an amount equal to H-gas demand plus blending capacity and at the same time minimize production from the Groningen field. This is also part of the small fields policy.
Initially, the storage operator operates two storage facilities: one H-gas facility (Grijpskerk) and one G-gas facility (Norg). Its operation algorithm determines production when Gasunie demand is greater than the resource operator's supply and injection when there is excess production capacity.
The storage investment algorithm is not used at the moment, because the Gasunie's demand for additional storage capacity goes to the independent storage operator. In reality, the quality of the depleted gas fields in the possession of the operators would be the deciding factor in determining the choice of operator. However, at present this is not part of the model and so is disregarded.

Finally, the *production contract agent's* bargaining algorithm determines the quantities, prices and flexibility in the production contracts. As mentioned above, the Gasunie-import contract is determined in the normal way, whereas the Gasunie-small field operator contract and the Gasunie-NAM contract are dictated by the resource operators under the constraints of the small field policy. The duration of the production contract is one year. However, to represent the special relationship between the NAM and Gasunie their contract is updated daily, giving Gasunie up-to-date information about the NAM's production capacity.

6.3.3 Data

The simulation covers twenty years, notionally from 2000 to 2020. Initial conditions are chosen to approximate the 2000 situation. However, as the availability of data is limited and in many cases confidential, the correspondence is rather imperfect. Data for resource operators are based on production forecasts published by TNO (2008). Data concerning transport were received from Gasunie. Parameters governing demand are based partly on confidential Gasunie data, partly on public ECN data (ECN, 2009). Behavioral parameters such as attitudes to risk have to be estimated and the sensitivity of the results obtained to variations in these parameters is discussed in later sections. The complete dataset is provided in Appendix II.

A general format for infrastructure is provided in the dataset, on the basis of which operators choose a quantity. This is mostly of importance for storages and prospects, as it limits the decision variables for investment. Second, initial conditions for transport capacity are not based on actual data but on initial adequacy. As the use of daily time steps in the simulation smoothes out the hour-to-hour differences, using actual transport capacity figures would introduce an upward bias. With regard to storages, it is assumed there are none available at the start of the simulation. This prevents an initial overcapacity, as storages may have been built to guard against peak winters, which are not part of the simulation. The choice of initial values for contracts is of limited importance, as they change after one year when actors have built up some memory. Initial infrastructure is more important, as it changes more slowly. Finally, with regard to demand, a price sensitivity of zero is assumed, as the historical trends in consumption on which demand is based are already a function of the price level.

6.4 Results from GasnetNL1

The results obtained from the GasnetNL1-model are displayed below in a series of eight figures. First, it will be ascertained whether the security conditions formulated in Section 2.6 are fulfilled. Figure 6.4 shows the actual development of supply and demand over time. It can be seen that demand for G-gas has a greater seasonal variation than demand for H-gas, with higher peaks in winter and lower demand in summer. This is caused by the higher dependence on temperature of G-gas consumption. The quantity condition is fulfilled throughout most of the simulation, but a few peaks in demand for both H-gas and G-gas occur which are not covered by supply contracts.

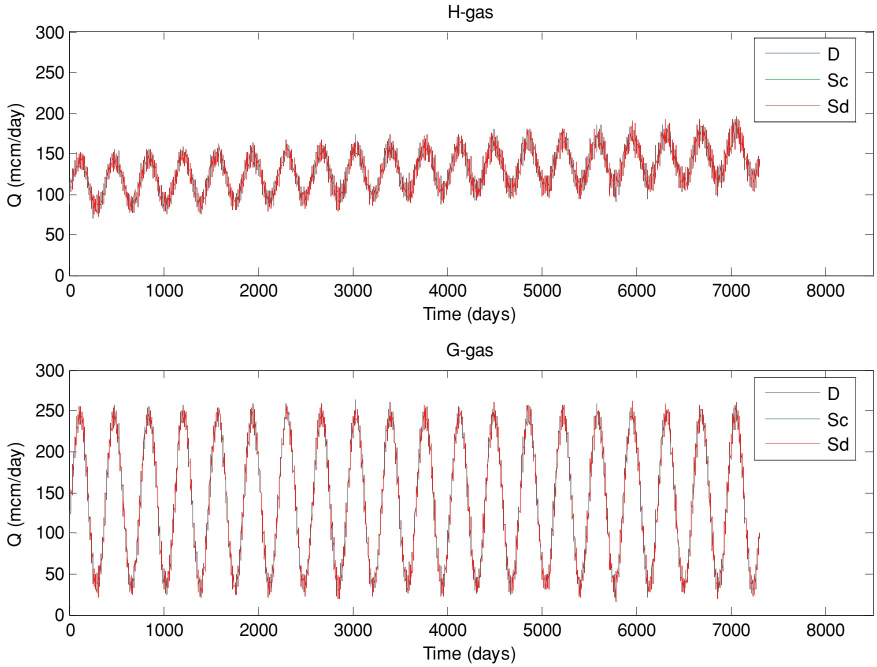


Figure 6.4: Supply and demand for H-gas (top) and G-gas (bottom).

Figure 6.5 shows the quantities offered and requested in supply contracts for H-gas and G-gas. Demand for H-gas contracts increases steadily over time, whereas demand for G-gas contracts is more or less constant. The supply of H-gas contracts is adjusted yearly to demand. As indigenous production capacity is in decline, the rise in demand is met by additional imports and storage. The initial overcapacity in G-gas is seen to decrease over the years, because of the depletion of the Groningen field. This is compensated by adding storage capacity. The spikes in both the H-gas and the G-gas contract supply lines are caused by the addition of storage facilities, the size of which necessitates some initial overcapacity. It can be seen that supply exceeds demand throughout the simulation. This means the sporadic contract shortages occurring are not due to a lack of contracts on offer, but to the insufficient purchases of users, which are in turn a function of users' contracting safety margins.

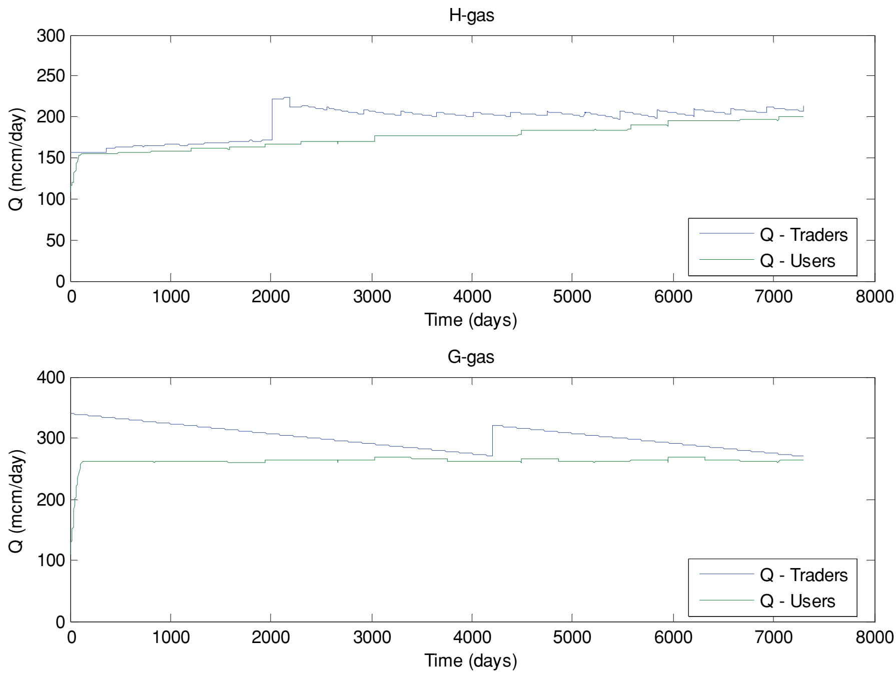


Figure 6.5: Supply contract quantities requested and offered for H-gas (top) and G-gas (bottom).

Figure 6.6 shows the system integrity and the buffer volumes of the Gasunie network and the LDC network. It can be seen that the integrity of all networks is preserved throughout the simulation. In other words, the physical condition is satisfied. The buffer volumes provide some insight into the tightness of the system. When buffer volumes are low, the system integrity is close to being breached. However, as the figure shows, buffer volumes are at their maximum almost continuously. This indicates that there is no lack of supplies.

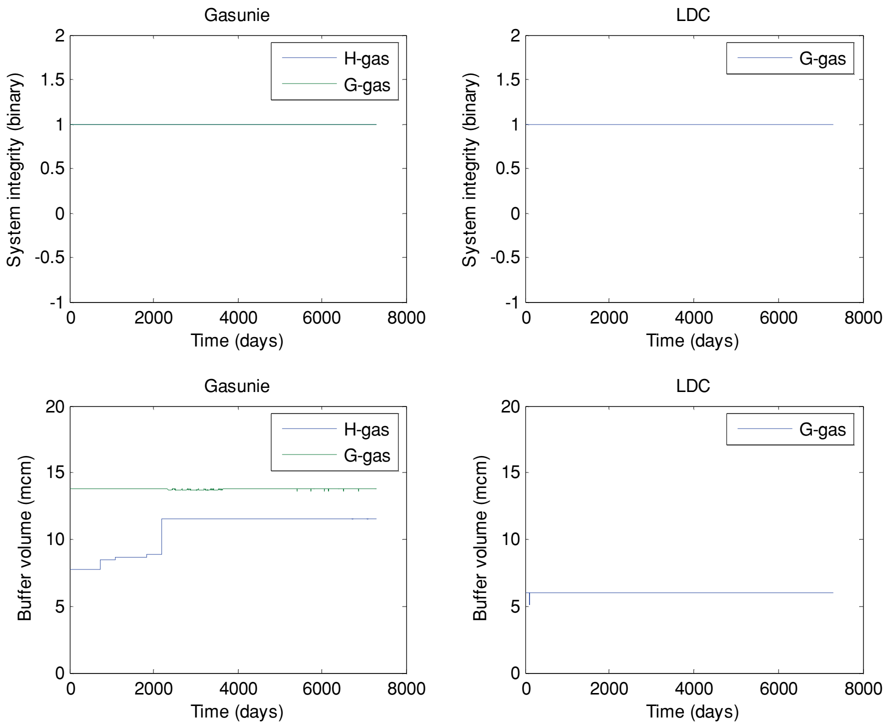


Figure 6.6: System integrity of the Gasunie networks (top) and the LDC network (bottom).

Figure 6.7 shows the development of prices during the simulation period. The upper graph shows the development of the oil price, which is a random variable with an upward trend and is input to the simulation. The six month average is obtained by taking the mean of the price in the six month period preceding the calculation day. This average is used as the basis for the oil index, which is shown in the lower graph. The other two lines in the lower graph show the contract prices for small and large end-users. Since these prices are formed by applying a markup to the oil-indexed price, they are higher than the oil-indexed price. In addition, the price for small end-users is higher than for large end-users, as they face an additional markup from the LDC agent. With regard to the price condition, it can be concluded that no sudden price increases are necessary to balance supply and demand. In the long term, however, the price rises to such levels that demand destruction may occur.

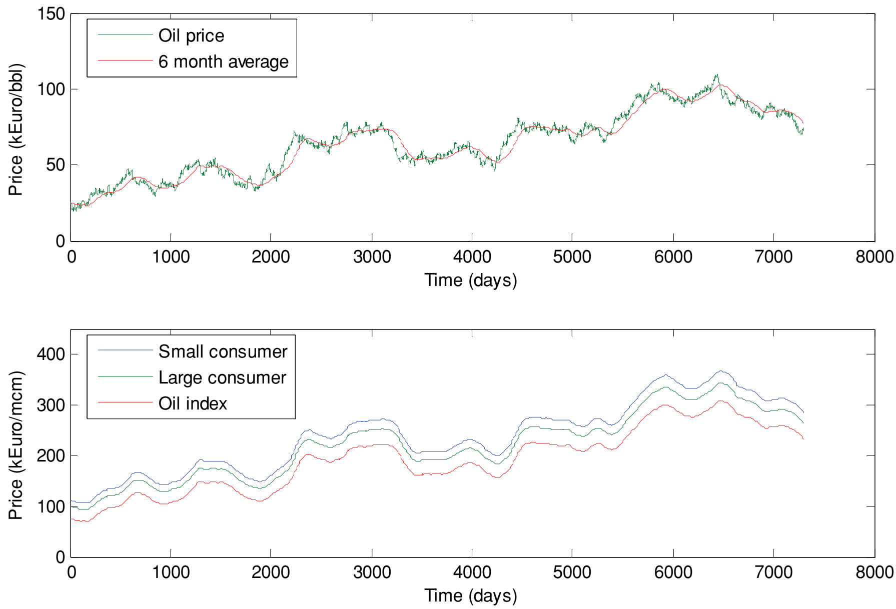


Figure 6.7: The development of the oil price, the oil-indexed gas price and end-user prices over time.

The results discussed above are quantified and summarized in Table 6.1. The averages of the three prices are shown, the oil-indexed price being the lowest, the large end user price somewhat higher and the small end-user price the highest. As in Chapter 5, the maximum acceptable price is set at 300 kE/mcm, which is equal to user income divided by average demand. This leads to a failure to meet the price condition for small end-users 22% of the time, and for large end users 16% of the time. As indicated above, the physical condition is met continuously, whereas the quantity condition is not met for only 2 days in the case of G-gas, and 7 days in the case of H-gas. This difference is caused by the growth of H-gas demand over time, as opposed to the constant average demand for G-gas.

Table 6.1: Performance indicators for the GasnetNL1 model.

Average price:	Small end-user	=	240.9 kE/mcm
	Large end-user	=	224.3 kE/mcm
	Oil-indexed	=	191.2 kE/mcm
Quantity condition not met:	H-gas	=	7 out of 7300 days
	G-gas	=	2 out of 7300 days
Physical condition not met:	H-gas	=	0 out of 7300 days
	G-gas	=	0 out of 7300 days
Price condition not met:	Small end-user	=	1668 out of 7300 days
	Large end-user	=	1181 out of 7300 days
	Oil-indexed	=	166 out of 7300 days

Next, a look can be taken at some of the variables underlying the results. In Figure 6.8, the sources of H-gas and G-gas supplies are shown. The top graph shows the shift of production from indigenous sources to import and storages. H-gas supply from the NAM and the independent small field operator peak after 6 and 13 years respectively. The resulting decline in domestic supply is filled by imports. It can also be seen that a flexible supply source, R3, is replaced by an inflexible source, R1. To compensate for this, a storage facility is built and taken into use after five years. Initially, production from and injection into the storage is highly monotonous, as witnessed by the flat shape of the line. This indicates the storage's operation is purely precautionary, i.e. the storage is filled in summer and emptied in winter according to a preset schedule. After a few years, the line becomes more erratic, which indicates the storage is being used to deal with real supply shortages and excesses.

A similar development takes place for G-gas, although in this case the decline in indigenous production capacity is more modest. A storage facility is built to maintain sufficient production capacity on peak demand days, but the storage can be filled completely from indigenous sources in summer. In other words, the volume available from indigenous sources is still adequate, but capacity is not.

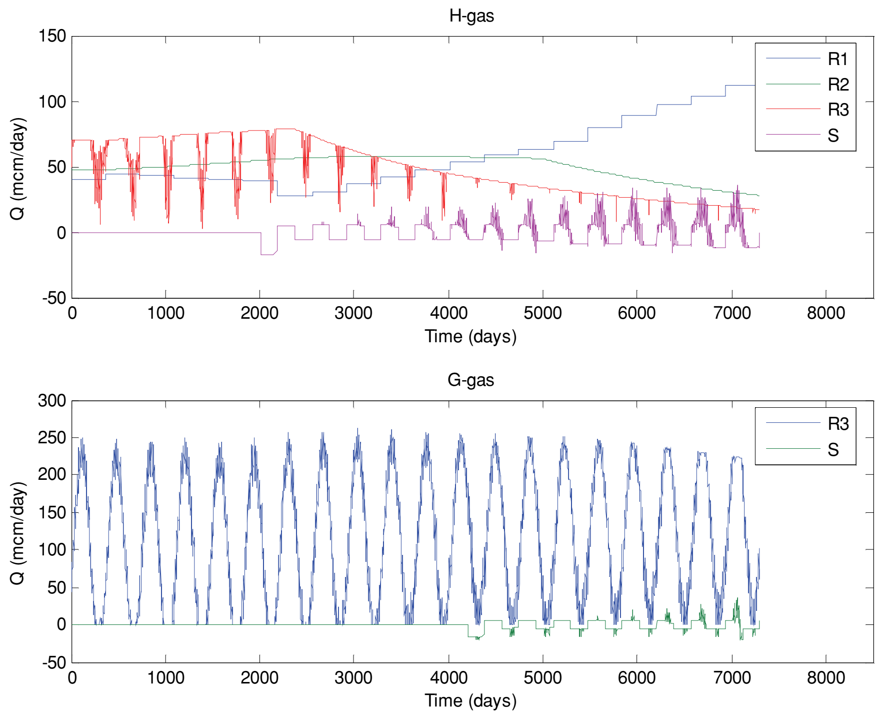


Figure 6.8: Production of H-gas (top) and G-gas (bottom).

Figure 6.9 provides some more detail with regard to the physical development of storage capacity, transport capacity and blending capacity. In the storage capacity graph, it is shown that one H-gas facility is built and one G-gas facility. In both cases, the minimum volume stored during the year starts off constant, which indicates a normal volume shifting pattern. In later years, the minimum volume stored starts to decrease, which indicates the storage facility is used more intensively.

The lower graph shows the physical development of Gasunie's and the LDC's transport networks. As demand for G-gas is more or less constant throughout the simulation period, no additions are required to Gasunie's G-gas network and the LDC's network. Therefore, no investment takes place and both capacities are constant. Due to the rising trend in H-gas demand, H-gas transport capacity must expand along with it. The investment peak around day 2000 coincides with the start up of the H-gas storage facility. Due to the rise in supply from inflexible sources, blending capacity is also expanded.

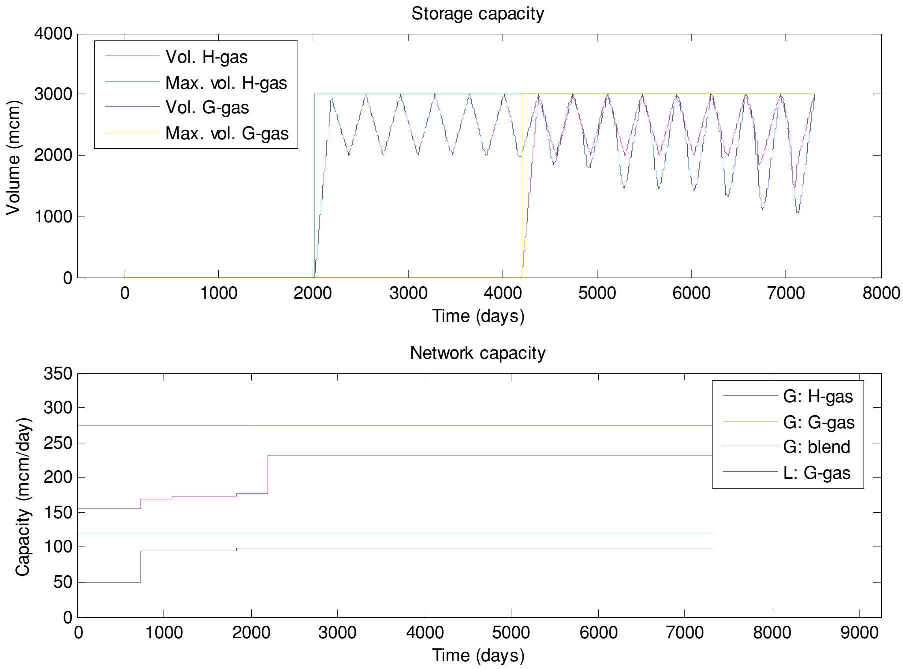


Figure 6.9: The development of storage capacity, transport capacity and blending capacity over time.

It should be noted that the difference in development between H-gas and G-gas transport capacity is partly caused by the structure of the investment decision algorithm. For G-gas, the algorithm is based on expected demand, which means production capacity can be, and initially is, much larger than transport capacity. In the case of H-gas, however, small field policy dictates that Gasunie must facilitate the production of H-gas at full capacity, which means expected supply determines transport capacity rather than demand.

Figure 6.10 shows the development of the money stock over time of all independent actor agents. The main thing to note from the lower two graphs is that all stocks rise over time, indicating that the system is stable, as companies will not go bankrupt. The relatively low rise of the Gasunie money stock and the high rise of the NAM's money stock are caused by the statutory rule that Gasunie makes a profit of 80 million Euros each year and passes on any excess profit to the NAM. The upper graph shows the users' money stocks. As oil prices rise over time, the gradient of the change in stocks decreases. In addition, the users with a more temperature dependent consumption see their stocks fluctuate more during the year, as can be seen most clearly in U3.

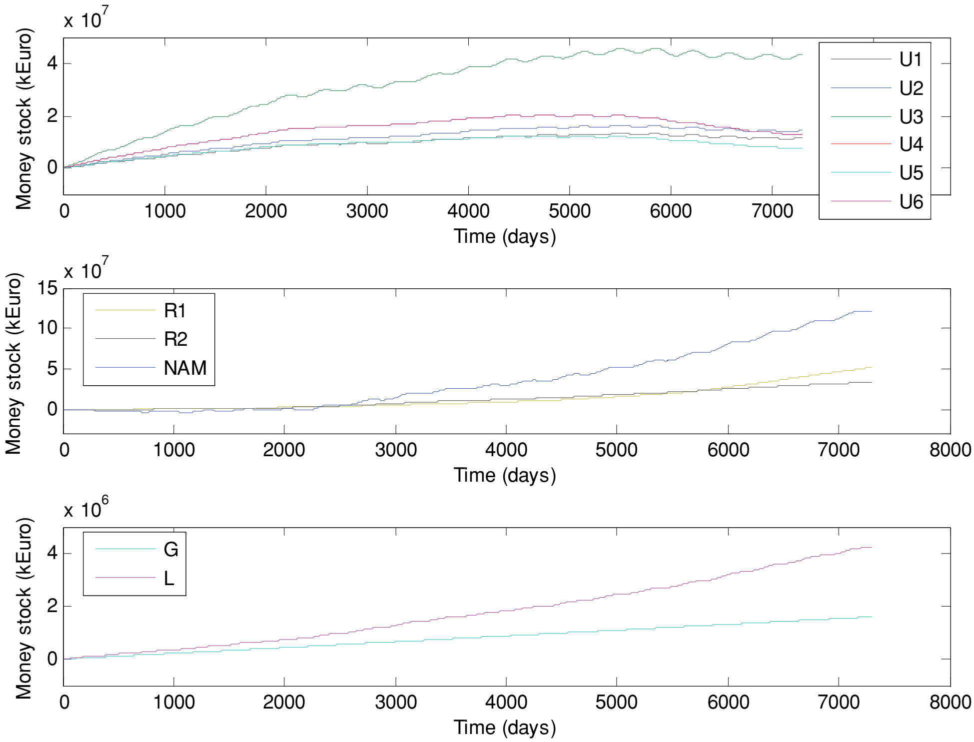


Figure 6.10: Money stocks of all independent actor agents.

Finally, Figure 6.11 shows the quantities contracted by users and the LDC over time. All are fairly stable over time, with some fluctuations caused by changing expectations. These expectations are in turn determined by demand in the recent past. The contracts for H-gas increase gradually, in line with the growth in H-gas demand.

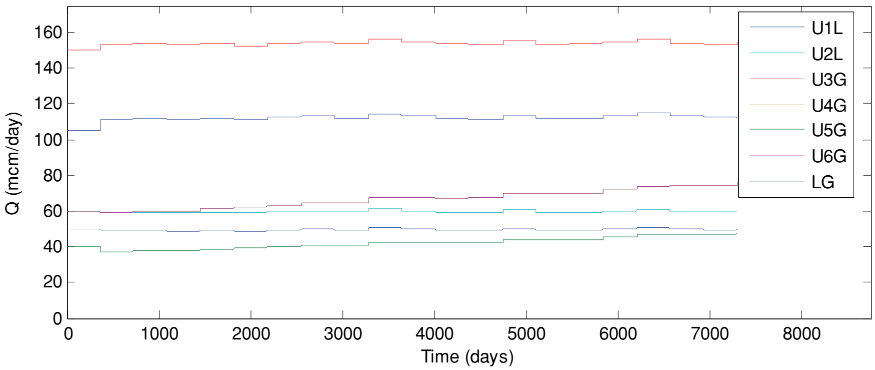


Figure 6.11: Contracts between users, LDC and Gasunie.

The results presented here provide a useful starting point for an analysis of the Dutch pre-liberalization market, but they require some more interpretation to be fully understood. Therefore, this section will conclude with a sensitivity analysis of the GasnetNL1-model.

The most striking aspect of the GasnetNL1 model is its centralized structure. Most of the decision algorithms are fairly simple and require little computational ability. Users contract supplies according to their needs, resource operators explore for gas where profitable and then produce at full capacity, and the LDC functions as a straightforward middleman. The most complex algorithm is therefore Gasunie's contracting algorithm. In this algorithm, it is decided how much to invest in storage facilities and transport capacity and how much gas to import. Gasunie is well suited to make these decisions, as all information about supply and demand in the model is available to the integrated agent.

It follows from this structure that the model is most sensitive to the structure of this decision algorithm and the parameters affecting it. However, irrespective of the actual parameters and algorithm structure, a fundamental tradeoff between affordability and security persists. When Gasunie wants to secure delivery at all costs, it will invest in storage facilities sooner, invest in more transport capacity, and contract more gas from foreign sources. Alternatively, it can minimize costs by investing and importing as little as possible. However, as demand is fundamentally uncertain, lowering costs implies increasing the risk of a supply interruption. As has been demonstrated in Chapter 1, it is debatable where the optimum of this tradeoff lies. It is, however, notable that this industry structure allows policy makers to implement their chosen optimum directly through their shareholdings in the Gasunie company.

The parameter which embodies this tradeoff is the contracting safety margin (Tcsm). Therefore, a sensitivity analysis is performed with regard to the value of this parameter. Figure 6.12 shows the buffer volumes of the H-gas and G-gas networks for five different values of the contracting safety margin (csm). In the base scenario, its value was 1.05. Results are shown for four alternative values as well: 1.00, 0.99, 0.98 and 0.95. It can be seen that the security of the system gradually declines with a lower safety margin. At csm = 1.00, small amounts from the buffer are used in the first five years. At csm = 0.99, usage is slightly larger in the early years, and system integrity is breached near the end of the simulation. At csm = 0.98, system integrity is breached once near the beginning of the simulation and for a longer period near the end. At 0.95, system integrity is breached repeatedly, both at the start and in the final three years of the simulation.

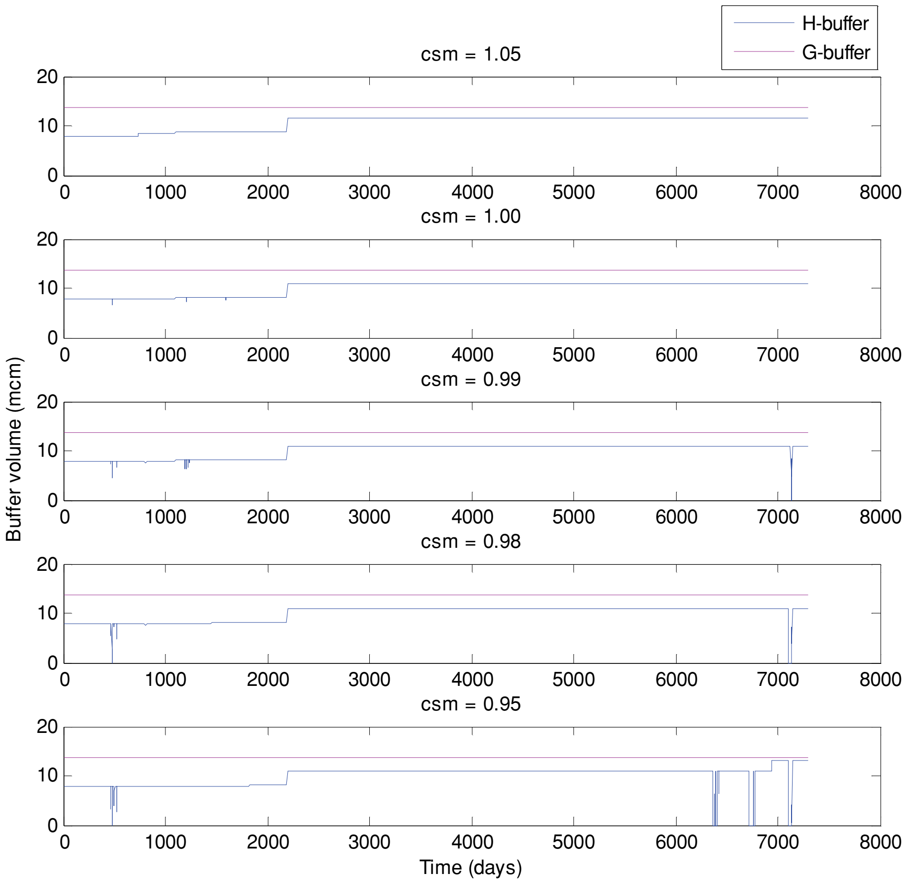


Figure 6.12: Sensitivity analysis, system integrity as a function of the contracting safety margin.

The effects of the changes in the csm parameter on the quantity condition and the physical condition are shown in Table 6.2. The values for the physical condition correspond to the frequencies of buffer volume depletion shown in Figure 6.12. The values for the quantity condition display a similar pattern. Initially, the increase in days for which the condition is not met is limited, but the number grows quickly for lower values of the csm.

A non-linearity is visible in the csm = 0.99 graph, where the buffer is used to balance supply and demand at the start of year four. This buffer use is absent in the other graphs, which suggests it is not a direct consequence of lowering the csm. The underlying cause of this non-linearity is shown in Figure 6.13, where user demand (D), is plotted together with the supply contracted by users (Sc). The difference between the two thus equals the demand for which no supply could be contracted by users. As the supply offered by Gasunie also depends on its csm, supply drops together with the csm, as can be seen by comparing the top graph with the bottom graph. This means the stress placed on the physical condition in the csm = 0.99 scenario is moved to the quantity condition for values below 0.99.

Table 6.2: Performance indicators for the GasnetNL1 model as a function of Gasunie's contracting safety margin.

csm	Quantity condition not met		Physical condition not met	
	H-gas	G-gas	H-gas	G-gas
1.05	7	2	0	0
1.00	10	2	0	0
0.99	21	2	8	0
0.98	29	2	37	0
0.95	43	2	112	0

The decrease in supply security following from a lower csm is compensated by a decrease in costs, i.e. an increase in affordability. In the GasnetNL1 model, this cost advantage ends up with the NAM. Therefore, its money stock increases faster in the case of a lower csm. This is shown in Figure 6.14, where the NAM's money stock is plotted for all five scenarios. Here, again, two effects oppose each other. The move from 1.05 to 1.00 only leads to efficiency gains, which translate into a large increase in the money stock. Additional decreases in the csm lead to further cost decreases, but are accompanied by integrity costs (because of system integrity breaches) and lower sales. Therefore, the money gained by moving from 1.05 to 1.00 is much more than the money gained by moving from 1.00 to 0.95. For the values of csm examined, the NAM's gains from reducing the csm outweigh its costs, but the additional damage costs imposed on users are not reflected in its money stock.

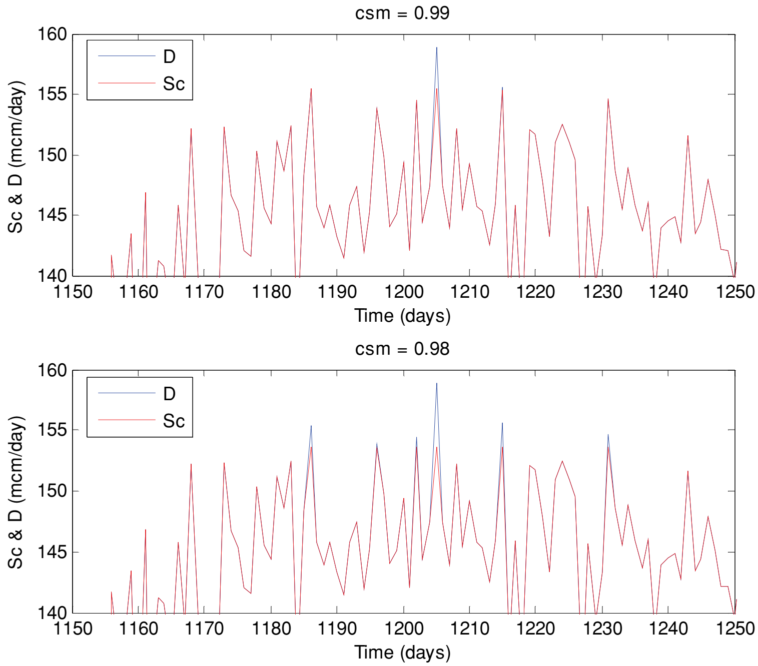


Figure 6.13: Sensitivity analysis, contracts as a function of the contracting safety margin.

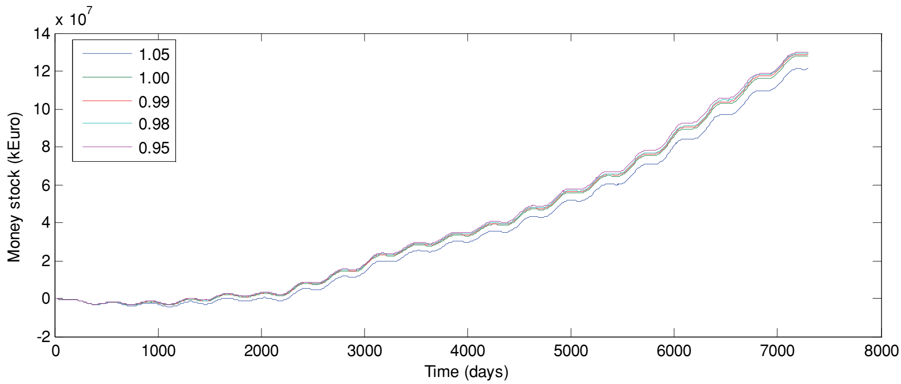


Figure 6.14: The NAM's money stock as a function of the contracting safety margin.

It can be concluded that the results from the sensitivity analysis are in line with expectations. They provide an example of the tradeoff between affordability and security as well as the tradeoff between private and public wealth. The next two sections continue the Dutch market study with an analysis of its post-liberalization structure.

6.5 The post-liberalization model: GasnetNL2

6.5.1 The agent network

The post-liberalization agent network differs from the pre-liberalization network in a number of significant ways. First, the integrated trader-network operator firms have been dissolved. This means that traders and network operators have become independent firms which are connected through a transport contract agent. The former Gasunie is split into a trading company, GasTerra, and a transport company, Gasunie. The former LDC is also split into a trading and a transport arm, but their transport arm is not included in the model, as it is of little relevance. Second, the monopoly on gas trading has been abolished, which means new traders have entered the market. All traders in the model must compete with each other for supplying users with gas. Third, some agents have extended their business into another part of the value chain. Consumers using gas for power generation have integrated with the trading arm of the former LDC's, creating an integrated user-trader agent. At the same time, some resource operators formerly supplying Gasunie have now chosen to market their gas themselves, or their fields have been acquired by traders entering the Dutch market, thus creating an integrated trader-resource operator agent. Fourth, the entrance of traders has lead to the foundation of a spot market, which can be used by traders to trade gas amongst themselves.

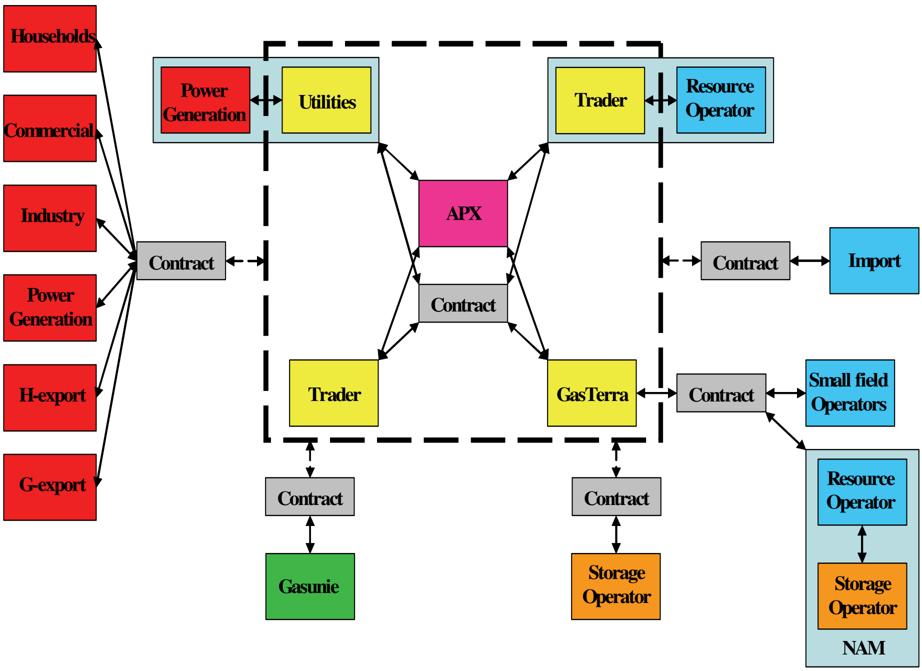


Figure 6.15: The GasnetNL2 agent network, representing the Dutch gas market after liberalization.

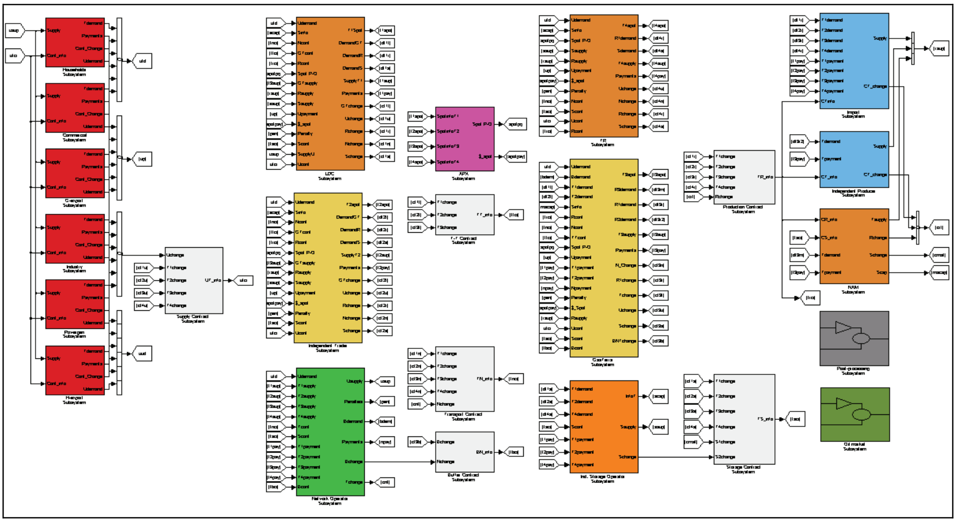


Figure 6.16: A screenshot of the GasnetNL2 agent network, representing the Dutch gas market after liberalization.

These differences prompt the construction of a new agent network, which is shown in Figure 6.15. The black square signifies that all four traders are connected to the supply, transport, storage and production contract agent. However, GasTerra still has an exclusive contract with the small field operator and the NAM. In total, 18 actor agents and 10 institutional agents are included in the model, comprising 15 independent firms. A screenshot of the actual Simulink model is shown in Figure 6.16. Most of the agents' decision algorithms are modified along with the shape of the agent network. In the next paragraphs, the decision algorithms of each agent in the GasnetNL2 model are described.

6.5.2 Agent behavior

The six *user agents* from GasnetNL1 are also used in GasnetNL2. The only adjustment required is the activation of their <u>switching algorithm</u>, which is part of the <u>contracting algorithm</u> and functions as described in Section 4.5.1. In addition, a seventh user agent is introduced as part of the integrated user-trader agent (see 6.6.3). To ensure the comparability of both models, the combined demand of both power generation agents is set equal to that of the single power generation agent in GasnetNL1.

The *user-trader agent* consists of a user agent and a trader agent, bound together by an integration agent. This means the agent has four decision algorithms: the user's demand generation algorithm, the trader's spot market trading and source selection algorithms, and the integration agent's contracting algorithm.
The user's <u>demand generation algorithm</u> differs from those of the other user agents, as it provides the trader with some additional information. As there is no contract

determining the maximum amount the user is allowed to demand (and the trader is obliged to provide), the user provides the trader with its demand, the fraction of its demand that is interruptible, and the price at which it would be beneficial for the user to do so. In this way, the user provides a simple demand curve which the trader can use to optimize its spot market trading and source selection behavior.
The trader's spot market trading algorithm produces one offer and two bids: a base bid and a peak bid. The base bid is the amount of gas the trader is willing to buy at a price below the price of its contracted gas, thereby substituting for other sources. The peak bid is the amount of gas it is willing to buy at a price above the price of its contracted gas, thereby complementing other sources when they are insufficient for meeting demand. The offer is the amount of gas it is willing to sell above the price of its contracted gas, thereby making a profit on gas it has contracted but does not need. In reality, there could be a second offer consisting of the amount of gas a trader wants to sell at any price, i.e. gas it needs to get rid of. However, this is not included in the model.
The trader's source selection algorithm allocates its demand between its import contract, its GasTerra contract, and its storage facility. As the import contract provides no flexibility, the trader always chooses this source first. The flexible GasTerra contract is ranked second, and the storage facility is ranked third, because its use is limited to the volume of gas stored inside it.
The integration agent's contracting algorithm determines the contract offer made to user agents and the contract request made to GasTerra, the import agent, Gasunie and the storage agent. The quantity offered to users is equal to their maximum past demand times a safety margin. The commodity price in the user contract is determined by adding a markup to the trader agent's commodity purchasing costs and the capacity price is determined by adding together the network operating costs and the capacity purchasing costs and then adding a markup. The DCQ's requested to GasTerra and the import agent added together are equal to the mean quantity demanded by users. Demand is divided evenly over these two sources. The required flexibility, i.e. the difference between peak demand and mean demand, is equal to the swing demanded from GasTerra and the number of storage bundles added together. Again, demand is divided evenly between these sources. Finally, demand for transport capacity from Gasunie is equal to the production capacity rented from the storage agent plus the DCQ of the import contract. Gas taken from GasTerra does not require transport capacity, because this is arranged by GasTerra.

The *trader agent* has three decision algorithms, a spot market trading algorithm, a source selection algorithm and a contracting algorithm, all of which are identical to the algorithms described in Section 6.6.3 for the user-trader agent. The only difference is that the independent trader does not benefit from the demand flexibility available to the integrated user-trader agent.

The *trader-resource operator agent* consists of a trader agent and a resource operator agent bound together by an integration agent. This means the integrated agent has five decision algorithms. The trader's spot market trading and source selection algorithms,

the resource operator agent's production and investment algorithms, and the integration agent's contracting algorithm.
The trader's spot market trading and source selection algorithm are largely identical to the algorithms described in Section 6.6.3 for the user-trader agent. The main difference is that instead of a contract with GasTerra, it has access to the production from the resource operator agent it is integrated with. This has two advantages. First, there are no contractual constraints to the amount of gas demanded, i.e. it has maximum flexibility. Second, it has guaranteed access to the supplies from the resource operator, because there is no competition for them from other traders. Third, it can offer gas on the spot market at a lower price than other traders, as its lower bound for sales is the cost of production rather than the contractual oil-linked price, thereby enabling it to capture market share.
The resource operator's production algorithm and investment algorithm are identical to those described in Section 4.5.3.
The integration agent's contracting algorithm determines the supply offer to users and the demand requests to the import agent, the Gasunie agent and the storage agent. The supply offer to users is equal to their maximum past demand times a safety margin. The request to the import agent is equal to the mean user demand minus the production capacity of the resource operator agent. This means that imports will be zero as long as production capacity is larger than mean demand. The request to the Gasunie agent is equal to the sum of the resource operator's production capacity, the contracted amount of import and the contracted amount of production capacity from the storage agent. Finally, the request to the storage agent is equal to the difference between peak demand and the combined supply capacity of the resource operator agent and the import contract.

The *GasTerra agent* is an independent trader agent, whose decision algorithms and position in the supply chain are similar to the Gasunie trader agent in the GasnetNL1 model.
The trader's spot market trading algorithm produces one offer and two bids: a base bid and a peak bid. However, GasTerra has no base bid, as it will always prefer gas from the NAM to the spot market. Its peak bid is used to augment supply when its own sources are insufficient. Its offer is equal to sum of the capacity available from import, small field operators, and the NAM, minus the capacity sold to users, traders and network operator.
The trader's source selection algorithm is used to choose between three sources of supply: import, small field operators, and the NAM. Flows from import and small field operators are held constant, as Gasunie purchases them without any added flexibility. It then tries to balance supply and demand by requesting the missing amount of supply from the NAM. An added complication is that the trader faces a demand for both H-gas and G-gas. Import and small field operators supply only H-gas, whereas the NAM can supply both. As the trader agent can use the network operator's blending capacity, it converts any excess H-gas into G-gas and in so doing minimizes G-gas production.

The trader's contracting algorithm determines the contract offer made to users, traders and the network operator, as well as the contract request to the import agent, the small field operator, the NAM and the network operator. The quantity offered to users, traders and network operator is equal to their maximum past demand times a safety margin. GasTerra still has limited influence on the quantities contracted from resource operators. As part of the small field policy, GasTerra is obliged to buy all gas offered to it by domestic producers. For this reason, the small field operator and the NAM set the quantities in their respective contracts. GasTerra does choose a quantity for the import contract. The quantity chosen is equal to the mean demand for H-gas minus the contracted supply from other sources, excluding storage. The prices (commodity and capacity) in the supply and buffer contracts are determined by GasTerra. The commodity price in the user contract is determined by adding a markup to GasTerra's commodity purchasing costs and the capacity price is determined by adding together the transport costs and the capacity purchasing costs and then adding a markup. The quantities requested to the storage operator are equal to the expected peak demand minus the peak capacity available from resource operators.

The bargaining algorithm of the *supply contract agent* (closed between users and traders) functions as described in Section 4.5.7, with one fundamental difference. The selling party determines the commodity price and the capacity price, but it is left to the buying party to choose the desired quantity. This modification is made o represent the fact that, in a competitive market, traders compete for market share and will not refuse a user a contract, even if they have not (yet) contracted the supplies to serve that user. The duration of the supply contracts is one year.

The *APX agent* represents a spot market where the H-gas commodity is traded on a daily basis. The notional location of the spot market is inside the Gasunie network. This means that traders who want to sell the commodity on the spot market must first acquire transport capacity to transport the commodity from locations of production (resource operators' reservoirs and storage operators' facilities) to the spot market. The spot market itself works exactly as described in Section 4.5.8.

After liberalization, the *Gasunie agent* consists of a network operator agent only.
The network operator's balancing algorithm compares user demand with trader supply in both the H-gas network and the G-gas network. Any unbalance is eliminated where possible with the help of the H-gas buffer and the G-gas buffer respectively. Whether this is successful or not determines the system integrity of each network. As the network operator is no longer integrated with a trader agent, supplies to fill the buffer are contracted through the buffer contract agent.
The network operator's investment algorithm for building additional H-gas transport capacity, G-gas transport capacity and blending capacity is still a function of past demand, expectations of future demand and a safety margin, as described in Section 4.5.5. However, estimating future demand has become more difficult than it was before liberalization. This is caused by the fact that more traders can now book

transport capacity and that these traders may have different plans or expectations than the network operator. Without integration, there is no guarantee that traders' bookings are in line with the network operator's expectations. Therefore, investment is not based on user demand for gas, but on trader demand for transport. Included in this demand is the availability of new storage facilities. As the lead time of storages is longer than the lead time of transport capacity, the network operator can ensure the availability of sufficient transport capacity for additional storages coming online.
The network operator's contracting algorithm determines the contract offer made to traders and the buffer bid made to GasTerra. The quantity offered to traders is simply equal to total available capacity. The price of transport capacity is regulated and is therefore a function of the value assigned to the network operator's assets (the regulatory asset base) and the permitted rate of return on the asset base. The size of the buffer contract is equal to the network operator's buffer capacity, which is itself a (constant) fraction of transport capacity.

The *transport contract agent*'s bargaining algorithm matches the supply and demand for transport capacity. As described in Section 4.5.7, in case of shortage transport capacity is allocated pro rata among bidding traders.

Again, the *buffer contract agent*'s bargaining algorithm functions exactly as described in Section 4.5.7. However, in contrast to the transport contract agent, the buffer contract is bilateral. For simplicity's sake and in accordance with the current situation, it is assumed GasTerra is the only supplier of buffer capacity to Gasunie.

The *import agent* functions in the same way after liberalization as before, but now (potentially) supplies all traders instead of Gasunie. As such, it still contains three decision algorithms: production, investment and contracting. However, the investment algorithm is not used, as modeling the investment process of foreign producers is beyond the scope of this model. Instead, an initial estimate is made of the volumes available for export to the Netherlands. These volumes are then modeled as the reservoirs available for production.
The contracting algorithm offers all available production capacity for sale to Gasunie at the oil-indexed price level. No flexibility is offered, as production is assumed to be too remote from the Dutch market to adjust to daily demand fluctuations timely.
An amount of gas equal to the contracted amount is then produced daily in the production algorithm.

The *small field operator agent*'s structure is also unchanged by liberalization. The investment algorithm represents exploration in the Dutch subsurface. Its investment is equal to the minimum of two quantities: the number of prospects expected to be profitable at current prices, and the internal means for investment available. It is assumed only H-gas is discovered and produced.
The contracting algorithm sets the daily contract quantity equal to production capacity. Again, no flexibility is offered, but not for technical reasons. The small fields

policy guarantees small field operators a constant, high load factor, which is reflected in the lack of flexibility in the contract.
Its production algorithm then sets daily production equal to production capacity for all producing reservoirs.

The *NAM agent* contains five decision algorithms: operation and investment in the storage operator agent, production and investment in the resource operator agent and contracting in the integration agent. Initially, the resource operator agent owns one G-gas producing field (Groningen) and one H-gas producing field (an aggregate of its small fields). Its investment algorithm is identical to the small field operator's algorithm, so only H-gas is added to its reserves.
Its production algorithm sets production equal to Gasunie demand. Gasunie demand consists of demand for H-gas and G-gas. Therefore, Gasunie sends information about available blending capacity to the NAM. This enables the NAM to maximize production from its small fields by producing an amount equal to H-gas demand plus blending capacity and at the same time minimize production from the Groningen field. This is also part of the small fields policy.
Initially, the storage operator operates two storage facilities: one H-gas facility (Grijpskerk) and one G-gas facility (Norg). Its operation algorithm determines production when Gasunie demand is greater than the resource operator's supply and injection when there is excess production capacity.
The storage investment algorithm is not used at the moment, because the Gasunie's demand for additional storage capacity goes to the independent storage operator. In reality, the quality of the depleted gas fields in the possession of the operators would be the deciding factor in determining the choice of operator. However, at present this is not part of the model and so is disregarded.

The *production contract agent*'s bargaining algorithm determines the quantities, prices and flexibility in the production contracts. As mentioned above, the Gasunie-import contract is determined in the normal way, whereas the Gasunie-small field operator contract and the Gasunie-NAM contract are dictated by the resource operators under the constraints of the small field policy. The duration of the production contract is one year. However, to represent the special relationship between the NAM and Gasunie their contract is updated daily, giving Gasunie up-to-date information about the NAM's production capacity.

The *storage operator agent* contains three decision algorithms: operation, investment and contracting.
Its operation algorithm functions largely as described in Section 4.5.4. The agent has the potential to operate H-gas storages as well as G-gas storages, which are included separately but treated in the same way.
The investment algorithm and contracting algorithm are based on an open season procedure, which means the storage operator agent first determines the price of a storage bundle and its investment threshold in the contracting algorithm. The interest of traders for this product is then tested in an open season procedure (see 6.6.17) and

results in a number of bundles being sold. This is input to the storage operator's investment algorithm, where the storage operator invests in a number of storages sufficient to cover demand.

The general structure of the *storage contract agent* is the same as before liberalization. There are still seven variables (price and six quantities) in the contract. The bargaining algorithm is modeled as an open season procedure. This means each trader has a demand for a number of storage bundles, based on the size and price of the bundle, which is determined by the storage operator. If the demand for storage bundles exceeds the storage operator's investment threshold, contracts are signed. This process determines the contract quantity five years ahead. After one year, the quantity five years ahead becomes the quantity four years ahead, etc.

6.5.3 Data
The dataset is chosen in such a way that it is identical to the dataset from GasnetNL1 where possible. Some differences arise because of the increase in actor agents (one user, two traders, one storage operator and one resource operator are added) and a change in institutional agents (two integration agents are removed and two others are added, furthermore, a transport contract agent, a buffer contract agent, a supply contract agent and a spot market agent are added). In the case of actor agents, each actor agent has its own set of parameters. Aggregate quantities such as average user demand for gas or resource operators' exploration capacity are unchanged, but they are distributed over more agents. In the case of institutional agents, initial contract values must be added and some new behavioral parameters are required because of the changes in actor agents' algorithms accompanying the different institutional agents. For example, the advent of a spot market requires traders to specify their spot trading strategies, and the introduction of transport contracts requires the network operator to set a penalty price for traders' imbalances.

6.6 Results from GasnetNL2
The results of the base run for the GasnetNL2-model are presented in a series of graphs similar to those presented in Section 6.4. Figure 6.17 is almost identical to Figure 6.4, as the input to the demand of user agents is unchanged. However, contracted supply does not match demand for five more days. This is caused by the added effect of switching, which can cause a user's demand to grow faster than its safety margin.

In Figure 6.18, the supply contract quantities requested and offered are shown. It can be seen that the quantities offered are now decoupled from physical supplies available. Instead, they are based on the traders' demand expectations. Therefore, they track demand more closely than in the previous model. The gap in the first year is caused by the initial absence of memory to base expectations on.

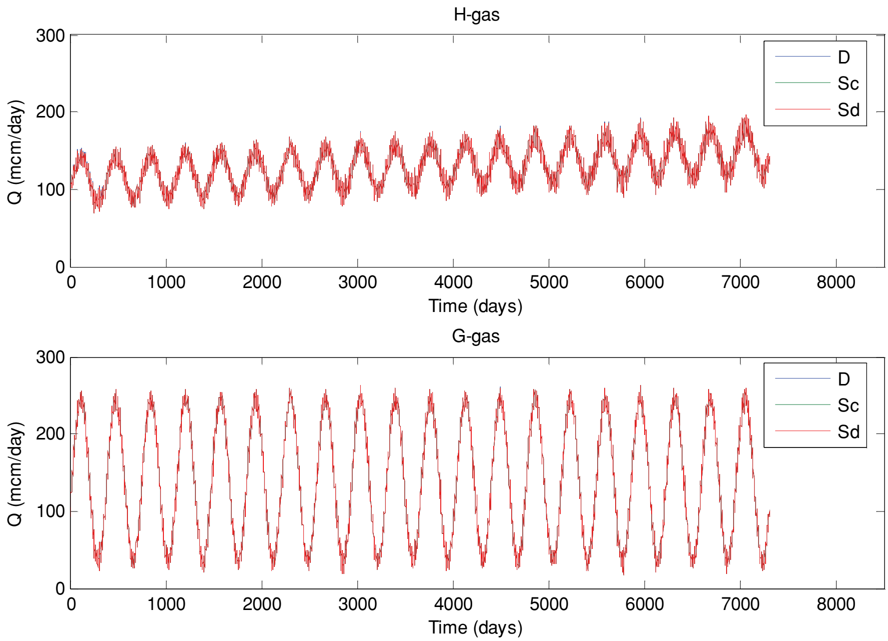


Figure 6.17: Supply and demand for H-gas (top) and G-gas (bottom).

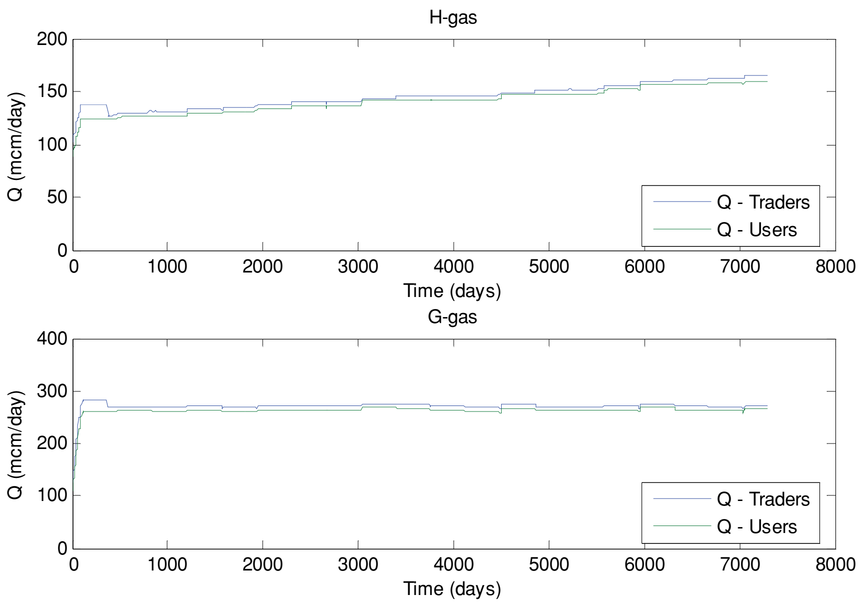


Figure 6.18: Supply contract quantities requested and offered for H-gas (top) and G-gas (bottom).

It should be noted that the contract market does not perform the same function as before liberalization, because traders will now agree to supply contract values higher than their offers, assuming that either the difference lies within their safety margins, or that they can purchase the additional gas needed on the spot market. Therefore, the quantity condition will not become a major bottleneck.

Figure 6.19 shows that system integrity is upheld throughout the simulation and buffer volumes are seldom used, which means there is still a sufficient margin for mitigating supply shortfalls.

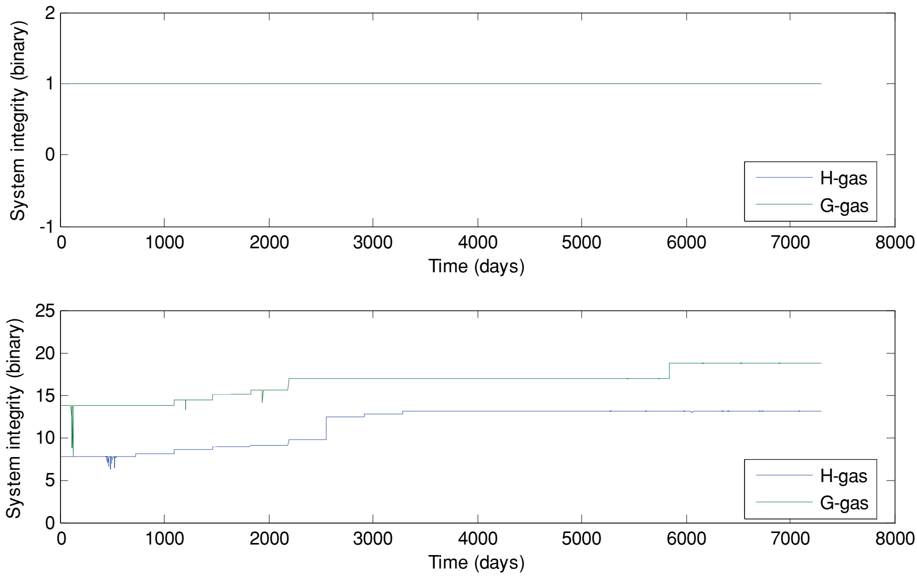


Figure 6.19: System integrity of the Gasunie network.

Figure 6.20 shows the development of prices in the GasnetNL2-model. As the same input is used for the oil price, the oil index is identical to the oil index shown in Figure 6.7. The spot price is the result of trade on the spot market. It can be seen that the spot price is strongly correlated with the oil index, but is far more volatile.

Roughly speaking, the spot price jumps between three levels. On average, gas is traded at a slight discount to the oil index, with price peaks in winter and larger discounts in summer. The initial prolonged peaks are caused by two factors. First of all, in the early years of the simulation, agents have to build up their memory and contract values have to settle into equilibrium. Second, storages are in the process of being constructed. As this takes five years, during this time a shortage of storage capacity can occur. Thereafter, the spot price is below the oil index more often and is traded at a larger discount on average. At this time, indigenous production is still substantial and storage capacity is abundant. In the final years, price peaks are higher and more prolonged. This is caused by rapidly decreasing indigenous production and, as a result, more scarcity in the flexibility market. Finally, consumer prices are still well above the oil index. As a large part of the traders' portfolios still consists of oil indexed supply contracts, prices are still a function of the oil index.

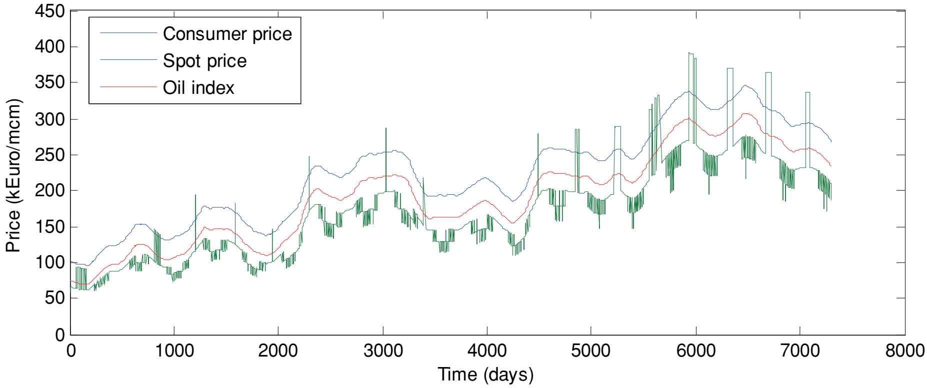


Figure 6.20: The development of the oil price, the spot price and end-user price over time.

Table 6.3: The performance indicators of the GasnetNL2 model.

Average price:	End-user	=	225.1 kE/mcm (volatility: 0.1 kE/mcm) (excl. small users: 224.2 kE/mcm)
	Spot	=	170.4 kE/mcm (volatility: 11.1 kE/mcm)
	Oil-indexed	=	191.2 kE/mcm
Quantity condition not met:	H-gas	=	12 out of 7300 days
	G-gas	=	2 out of 7300 days
Physical condition not met:	H-gas	=	0 out of 7300 days
	G-gas	=	0 out of 7300 days
Price condition not met:	End-user	=	1195 out of 7300 days
	Spot	=	265 out of 7300 days
	Oil-indexed	=	166 out of 7300 days

The performance indicators following from these results are shown in Table 6.3. As discussed above, the physical condition is met continuously and the quantity condition is met slightly less often than in GasnetNL1. In this model, it is necessary to look at spot prices as well as end-user prices to assess affordability, because the integrated user-trader can now buy its gas directly on the spot market. The average oil indexed price is necessarily the same as before liberalization. The end-user price is composed of the prices charged to large and to small users. To facilitate the comparison with GasnetNL1, the price excluding small users is also provided. Prices do not correspond perfectly to pre-liberalization prices, because the distribution network operator is not included in the post-liberalization model. However, it is clear that prices are more or less at the same level as before liberalization. The spot price is on average significantly lower than the oil indexed price, but also more volatile.

As in Section 6.4, a look can also be taken at the variables underlying these results. Figure 6.21 shows the development of the origin of H-gas and G-gas supplies over time. When comparing this figure to Figure 6.8, the same trends can be discerned, but with two notable differences. First, the role of storage is more prominent at an earlier time. Second, imports are higher initially, at the cost of indigenous production. The reason for both differences lies in the traders' contracting algorithm. Before liberalization, it was in Gasunie's interest to maximize production from indigenous sources and minimize imports and investments in storage. However, after liberalization, it can be beneficial to traders to diversify their portfolios and replace indigenous supplies with imports and storage.

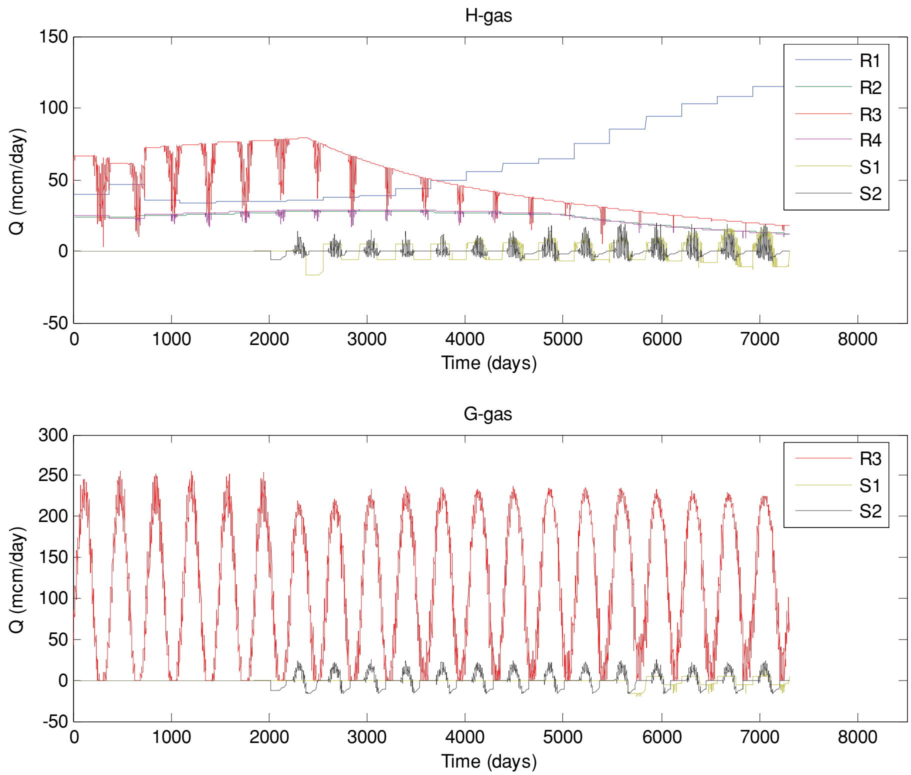


Figure 6.21: Production of H-gas (top) and G-gas (bottom).

Figure 6.22 again shows that investments in storage take place earlier and are larger. The development of network capacity also shows some different developments. As investments in transport capacity are now no longer based on expected user demand but on expected trader demand, investments in both H-gas and G-gas capacity are made. This need for additional transport capacity again arises from the traders' decisions to diversify and acquire gas from different sources. Investments in blending capacity, on the other hand, are lower, which is caused by the decrease in domestic production.

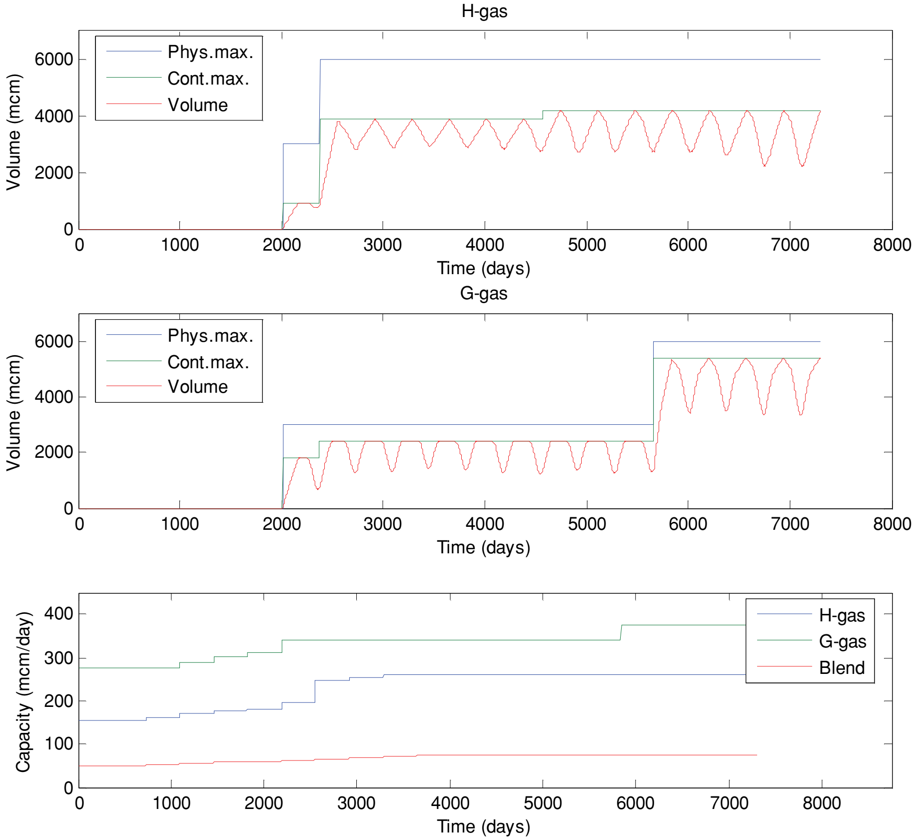


Figure 6.22: The development of storage capacity, transport capacity and blending capacity over time.

The development of money stocks is shown in Figure 6.23. The money stocks of users are similar to those before liberalization. The graph with money stocks of traders shows that those traders which are independent have a steadily increasing money stock, whereas the rise in prices negatively affects the trader integrated with a user (T1) and positively affects the trader integrated with a resource operator (T4). There is one money stock which steadily decreases over time, which is the money stock of the independent storage operator. This is caused by the fact that the number of bundles the storage operator has sold is too low to recover costs. This result can be interpreted in different ways. It could signify that storage operators might incur losses on their investments. Alternatively, the storage operator may in reality not invest at all, or build smaller storages.

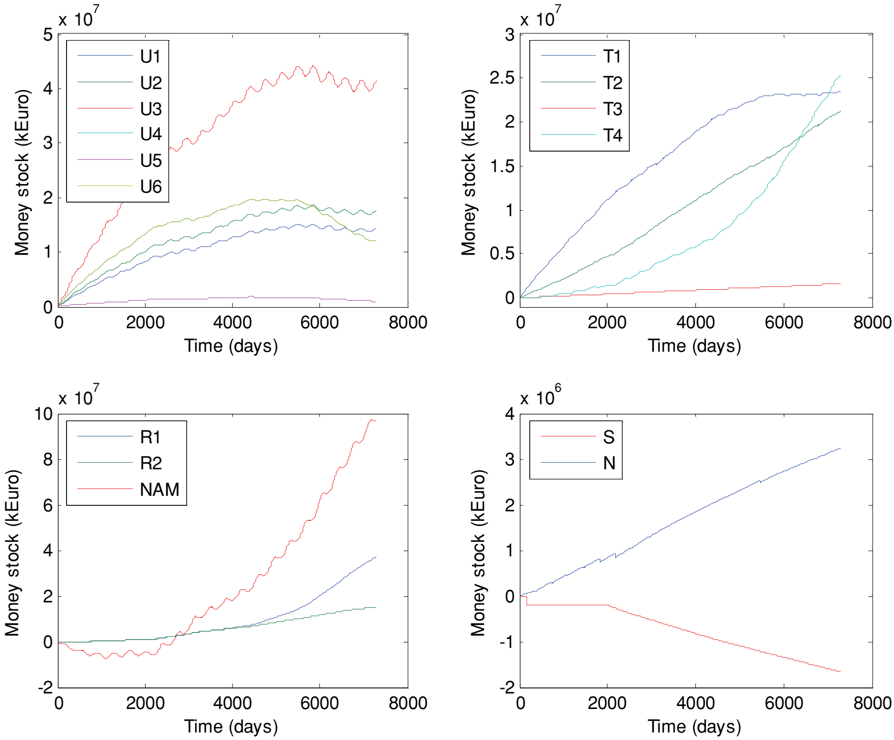


Figure 6.23: Money stocks of all independent actor agents.

Finally, Figure 6.24 shows that the contracts closed between users and traders vary more over time than before liberalization. This is caused by the possibility for users to switch from one supplier to the other. In the figure, the contracts of the "industry"-user (U4) are shown as an example. On the left, it is shown that GasTerra loses some of its market share to the other traders, mainly to the trader integrated with a resource operator (T4). However, due to rising demand for H-gas, the sales of GasTerra remain more or less constant in absolute numbers.

This result can be explained as follows. In this model, users will only switch because of a difference in contract price. As traders buy their gas mostly from the same sources, it is difficult to gain a cost advantage. One option is to use storages for flexibility, instead of the more expensive flexibility in the GasTerra supply contract. Another option is to gain access to production, and sell it at a discount to the oil indexed price. However, this last option is only available to those traders that are integrated to a resource operator. GasTerra's position is rather precarious, as it has a dominant position in the wholesale market and access to the cheapest sources of gas. In theory, it could therefore engage in price competition to drive out its competitors. However, it is assumed that it will not do so, as the competition authority would not allow this. Therefore, GasTerra sets a relatively high price, making large profits at the cost of losing market share.

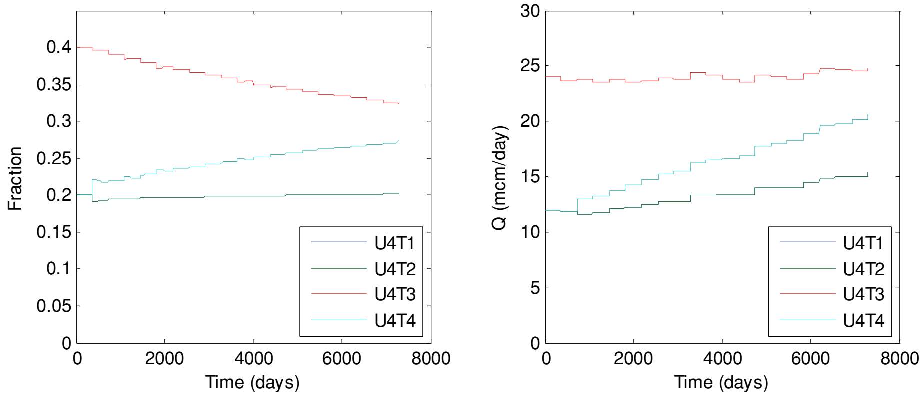


Figure 6.24: Contracts between users and traders.

To gain some insight into the dependency of model results on the dataset, this section concludes with a sensitivity analysis similar to the one performed in Section 6.4. However, Gasunie's contracting safety margin is no longer the central parameter in the model. Not only do the transport and the trading arm each have their own csm in this model, other traders and the independent storage operator have their own csm's too. The importance of the network operator's csm is discussed in Section 7.3, and that of the traders' csm's is investigated in Section 7.4. Therefore, this analysis will focus on the sensitivity of model results to the storage operator's csm. It has already been noted that the storage operator incurs losses throughout the base simulation. Therefore, its investment threshold is increased to see the effect on its performance.

Figure 6.25 shows the storage operator's money stock as a function of its investment threshold. It can be seen that the higher its investment threshold, the higher its resulting money stock is. This is caused by the limited demand for storage from traders, which does not reach a level high enough to sell out one complete facility during the simulation. Given its modest profit margin (15%), the storage operator needs to sell at least nine out of ten bundles to have a positive cash flow. However, at the end of the simulation, total demand for H-gas storage is no more than four bundles and demand for G-gas no more than eight.

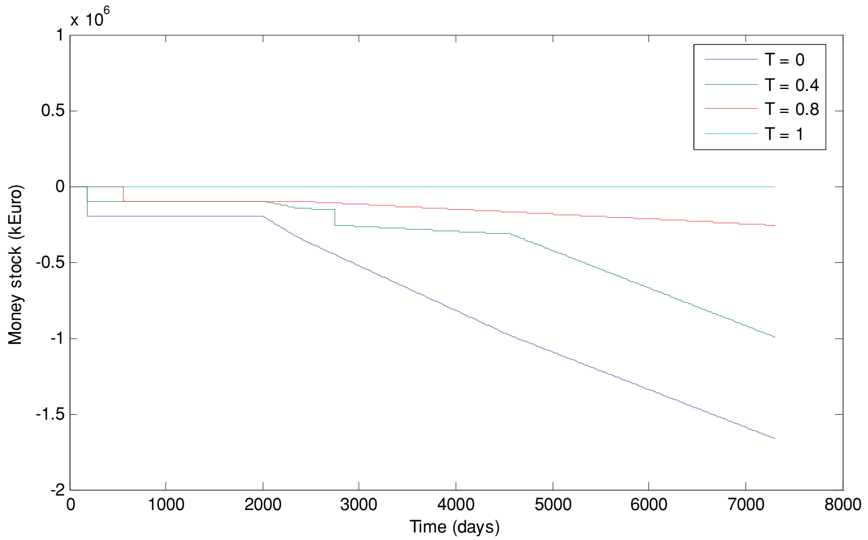


Figure 6.25: Storage operator money stock as a function of its investment threshold.

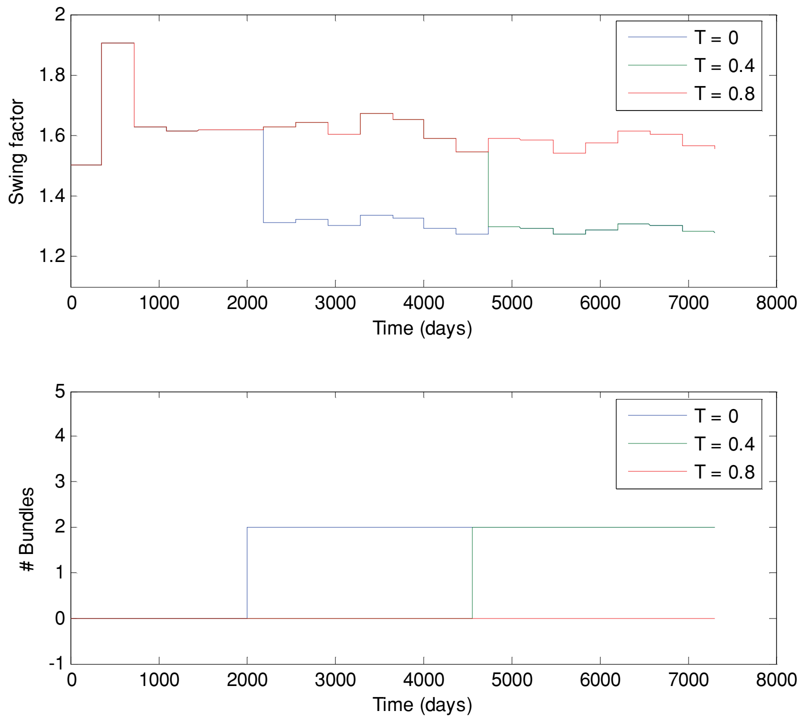


Figure 6.26: Substitution of swing for storage in a trader portfolio.

Part of the reason for this limited demand for storage is the competition in the flexibility market between storage and contractual swing. As contractual swing is provided by GasTerra, it is indirectly provided by the NAM's storages. Figure 6.26 shows the integrated User-Trader's two flexibility sources, i.e. its contractual swing factor and its storage bundles. When bundles from the storage operator become available, the trader reduces its swing factor in favor of those bundles. However, when the threshold to invest is higher, bundles become available later on in the simulation (or not at all), which means the swing factor remains high for a longer time.

In other words, the market cannot absorb two storages of this size, and the traders' choice to diversify flexibility sources means both storages are underutilized. In reality, this may prompt the construction of smaller storages than the one used here. The resulting situation is in line with results from an investigation by ILEX (2005) into the British market for storage, where it is concluded that there is no commercial case for building an additional storage the size of the Rough storage, which is of similar size as the storage facility used here, even though building it would have been economically efficient. A number of smaller storages have been built instead.

6.7 The impact of liberalization on affordability and supply security

In this chapter, The ENETSIM methodology was applied to study the liberalization of the Dutch natural gas market. The pre- and post-liberalization structures of the market were analyzed by constructing two agent networks. In this section, the findings from both models are used to perform a general assessment of liberalization.

First, a short recap is provided of how the three key liberalization policies identified in Section 2.3 are incorporated in ENETSIM.

1. Unbundling: In ENETSIM, unbundling entails a switch from integration agents to contract and market agents. The direct consequence of this is the replacement of a single decision algorithm for the integrated entity by two separate decision algorithms for the unbundled companies. The expected behavior of the counterparty must be integrated into these decisions. Since this behavior is at least partly unknown, unbundling introduces a source of uncertainty into the market. This uncertainty has to be translated into the decision algorithms by introducing a certain willingness to take risk. Furthermore, the introduction of a spot market reduces the importance of contracts, by offering an alternative source of and/or outlet for gas. It also reduces the information contained in the demand for and supply of contracts. Market players can forego the opportunity to close a contract to trade on the spot market instead. In terms of the security of supply conditions formulated earlier, risk shifts from the quantity condition to the price condition and the physical condition. This risk is especially important in two areas: investment and contracting. In the case of investment, there is a risk involved in investing in assets which have not yet been sold. In the case of contracting, there is a risk involved in entering into an obligation which may be impossible to fulfill.

Similarly, the network operator's legal obligation to balance the network is risky because it depends on traders to balance their input and output.

2. Competition and TPA: In ENETSIM, competition means that several agents of the same type perform their activity for their share of the market. Possible changes in these market shares create uncertainty, forcing companies to frequently adjust their contracts. Some economies of scale are foregone, because each company services only a part of the market. Furthermore, the margin applied to a product depends on the perceived competition. Since gas demand is highly inelastic, switching between suppliers is the main factor that prevents high margins rather than demand destruction. Therefore, switching propensity is a crucial new model parameter. Finally, it should be noted that the phenomena of cost reduction and innovation are not incorporated in the model, which introduces a possible bias in the results.
3. Government role: The role of government is mainly reflected in ENETSIM in the optimization objectives and constraints of actor agents. When the government is a shareholder with access to the boardroom, this can be represented by defining the government's objectives as the agent's objectives. However, when the government acts as a regulator, the agent's objective is some type of profit maximization and the regulator only determines the optimization constraints.

The effects of these model changes on performance can be ascertained through a comparison of the GasnetNL1-model with the GasnetNL2-model. A first observation is that the pre-liberalization structure is much simpler and more centralized than its post-liberalization counterpart. It is therefore also easier to assess its performance. With regard to affordability, its performance depends mainly on the oil price. For example, 75-90% of the large end-user price consists of the oil price, depending on its absolute value. With regard to security, the Gasunie functions as a gathering point for all information, on the basis of which the desired level of security can be chosen and implemented.

The GasnetNL2-model differs fundamentally from the GasnetNL1 model. It is characterized by the dispersion of the system's main functions over several agents. This dispersion is a double-edged sword. On the upside, it facilitates competition, thereby creating incentives for agents to improve their performance and increase affordability. Although affordability is still heavily dependent on the oil price, some decoupling can occur on the spot market in the case of supply shortages or excess supplies. Shortages are likely to occur when traders have under-contracted, whereas excess supply is the consequence of overcapacity in production. Decoupling can also occur when gas is deliberately sold at a discount to oil indexed gas to gain market share. The main driver in this case is whether competition between resource operators develops or not. However, as indigenous production capacity is set to decline, and foreign supplies are becoming concentrated in fewer hands, the outlook is not promising. On the downside, dispersion creates risks to supply security which arise from the possible lack of coordination between independent agents. In the face of uncertainty, there is no unique behavioral optimum for agents to choose, and they must select a degree of risk based on their risk tolerance. An agent's attitude to risk therefore becomes a key determinant of its behavior.

A clear example of such a novel security risk is the case of transport. As the network operator has been unbundled from trade, the nature of its investment decision has fundamentally changed. Rather than anticipating future demand for gas, the network operator must now anticipate the future behavior of traders. As traders may have widely varying strategies, which are also confidential, anticipating the demand for transport capacity has become more difficult. Furthermore, a new commercial risk to the network operator has come into existence, which is that its transport capacity will remain unsold. Roughly the same argument applies to the storage operator, which also faces the risk of unsold capacity. A related issue arises for traders, which have to contract supplies on the basis of demand expectations. Contracting the wrong amount of supplies can be costly. If too much supply is contracted, it may have to be sold at a price below purchasing costs, while contracting too little supply may necessitate buying supplies at a premium later on. Therefore, flexibility is essential. However, flexibility also comes at a price. Therefore, the trader faces its own tradeoff between affordability and security. And since traders compete with each other for market share, which is in turn a function of price, they will be inclined to weigh affordability more heavily than a monopolist (such as Gasunie before liberalization) would do.

Summarizing, the security of the post-liberalization market depends on the willingness to take risk of the agents involved. In the case of network operators and storage operators, investment has become more risky. This means that, at a constant willingness to take risk, supply security decreases with liberalization. In the case of traders, competition increases their willingness to take risk and thereby leads them to reduce their safety margins. This again means that supply security decreases with liberalization.

It can be concluded that liberalization produces a tradeoff between affordability and supply security. Whether liberalization can be considered a successful policy therefore depends on the weight that is attached to the additional security risks created versus the possibility of a decrease in the consumer price. Given the fact that liberalization favors affordability at the cost of supply security, policy makers would be well advised to redress the balance towards supply security. This would entail limiting the risks of investment in infrastructure rather than the quantity, and mitigating the risks created by traders.

The study of the Netherlands is continued in Chapter 7, where the Dutch post-liberalization market is subjected to a scenario analysis.

7. A scenario analysis of the Dutch natural gas market

7.1 Scenario selection

As outlined in Section 6.1, this chapter continues the study of the Dutch market. Whereas Chapter 6 consisted of a comparison between the pre- and post-liberalization structures of the market, this chapter takes the post-liberalization structure as a given and constructs three scenarios for the future of the Dutch market based on this structure.

Model development in ENETSIM proceeds in three steps. First, an agent network is chosen. Second, each agent's decision algorithms are specified. Third, a dataset is provided, consisting of a model's parameters and initial conditions. The selection of suitable scenarios will take place in the second and third step. Scenarios are a useful way to group together a large number of uncertainties in behavior and parameter values, the individual adjustment of which would require an unfeasibly large amount of model realizations. The model run performed for the GasnetNL2 model in the previous chapter can be characterized as a business as usual scenario, as it simply extrapolates the current situation to the future. However, a distinct possibility is that the future will be qualitatively different from the present, meaning that a simple extrapolation is no longer adequate. This chapter tries to capture the uncertainty about such qualitative changes by exploring three developments which, if realized, would each constitute a trend reversal.

An important source of uncertainty lies in the development of factors that are exogenous to the model used. From the summary of Dutch natural gas policy in Section 6.2, it can be observed that there are two major trends unfolding in the Dutch market environment. These are the transition to a more sustainable energy system and the formation of a gas roundabout. These trends will be referred to as "transition" and "internationalization" respectively. For each trend, a scenario will be constructed in which the possible consequences are investigated.

Another source of uncertainty is the specification of agent behavior *within* the model used. This uncertainty arises not from developments in the market environment, but from possible changes in the behavior of market parties. For this group of decision algorithms and parameters, another scenario is constructed. In the GasnetNL2 base scenario, parameters and behavioral algorithms are equal to those in GasnetNL1. This means they are chosen rather conservatively. In the free market, companies are more likely to constantly seek cost advantages, optimize their behavior and push their boundaries to defeat their competitors. In other words, their behavior will change in response to the free market environment. Therefore, this trend will be referred to as "responsivity".

The point of departure for all three scenarios is the GasnetNL2 model, i.e. its agent network, decision algorithms and dataset, as described in Section 6.5. This means the basis of each scenario is a liberalized market, calibrated to the Dutch situation in the year 2000. This includes an extensive resource base nearing a decline, substantial import and export, the co-existence of two gas qualities (H-gas and G-gas) with their own networks, an expected demand growth of 1.5% for H-gas and an expected constant demand for G-gas. This also implies that the price chosen to satisfy the price condition remains constant at 300 kE/mcm. The adjustments made to this "business as usual" scenario for each of the scenarios mentioned above and the results following from them are described in detail in the next sections.

7.2 Transition scenario

The transition to a sustainable energy system has been stated as the main goal of both European and Dutch energy policy in recent years. Dutch transition policy rests on three pillars: 20% energy conservation by 2020, 20% of energy obtained from renewable sources in 2020 and a 30% reduction in CO_2 emissions by 2020 (exceeding the EU's minimum target of 20%). However, it remains to be seen whether the government will be willing and able to take the measures necessary to reach its targets. The approach taken in defining this scenario is to assume that this transition will proceed as planned and that all the targets set by the government will be achieved. It will then be possible to see what the consequences are for the natural gas market.

To this end, three changes are applied to the business as usual scenario described in Section 6.5:

1. *Demand volume.* A shift in the fuel mix toward more sustainable sources combined with conservation policies will affect the demand for natural gas. There will be some demand destruction by substitution for wind, solar and biomass, and there may also be some substitution between fossil fuels, i.e. between natural gas and coal. The AER (Algemene Energieraad) explores the consequences of both policies in a recent report on the future Dutch fuel mix for power generation (Algemene Energieraad, 2008). The AER uses a 1% growth of energy use in its 2% conservation scenario. (With regard to the energy conservation target, it should be noted that the target is not absolute, but relative to the status quo. This means that if 3% demand growth is expected, the target becomes a growth of 1%. Since expectations are based mainly on projections of economic growth, these are highly uncertain, particularly in light of recent economic developments.) Current expectations for Europe as a whole are somewhat higher at 1.4% growth p.a. (EIA, 2008), which is caused mainly by an expected increase in the use of gas for power generation. However, such an increase is not expected in the Netherlands (Algemene Energieraad, 2008). An increase of 1% p.a. would amount to a 22% increase in 20 years. Given that supply from renewable energy sources should by then cover 20% of demand, the energy supplied by fossil fuels remains roughly constant. Based on the conservation measures envisaged, conservation will most likely be spread evenly over different user groups in

the Netherlands (Daniels et al., 2006). Therefore, it is assumed that the annual use of natural gas remains constant throughout the simulation.

2. *Demand volatility*. Sustainable power sources such as wind and solar depend on the weather for their power and supply from these sources is therefore volatile and inflexible. An increase in the use of these sources will therefore increase the volatility of the residual demand for natural gas. To represent this, the volatility of user demand is increased. The effect of this change differs per user group. The increase in volatility of demand for power generation will be most pronounced, as large scale wind power will play a large role there. The AER estimates that the installed capacity will be about 7 GW in 2020. Soens (2005) estimates that, on average, wind power produces at 30% of maximum capacity, with extremes of 0% and 100% of capacity. As power demand ranges from 11 to 24 GW (Algemene Energieraad, 2008), 0% to 60% of demand is met by wind power. This implies a residual demand for other fuels ranging from 4 to 24 GW, with an average of around 15 GW. Demand from industry is assumed to be unaffected, as industrial processes require a stable and continuous energy supply. Demand from households and businesses can be expected to become a bit more volatile because of the introduction of (micro-) CHP, solar panels and small scale wind. In the base scenario, the random variable for each user was assigned a variance of 10% of average demand. On the basis of the above considerations, the percentage for power generation is gradually increased from 10% to 60% over the duration of the simulation and the random variable for households and commercials increases from 10% to 20%. As G-gas is mainly used by households and commercials, and H-gas by a mixture of industry, power generation and small consumers, the percentage for G-export is raised to 20% and the H-export percentage is raised to 40%.
   In addition to changing the percentages, the formula relating the random variable to total demand warrants closer attention. An equally plausible alternative to multiplying percentages with average demand is to multiply them with actual demand. This means volatility is higher when demand is high and lower when demand is low. As available data are insufficient to choose between these options, runs are performed for both (denoted as the D-average and D-actual scenarios) and results are compared.
3. *Domestic gas production*. An alternative to retrieving natural gas from the subsurface is to produce gas from organic materials, known as biogas or green gas. In the coming years, this technology could become an additional gas source of substantial size. This is incorporated in the model as an additional gas source for domestic producers. The PNG (Platform Nieuw Gas) estimates that 10% of gas supply in the Netherlands could be covered by sustainable forms of gas in 2020 (Platform Nieuw Gas, 2007). This would entail fermentation of biomass to create biogas (amounting to 1-3% substitution in the short term) and gasification of biomass to create synthetic natural gas (amounting to 8-12% substitution in the long term). As average consumption in the base scenario is in the range of 350-400 mcm/day, this

entails a production of 35-40 mcm/day, i.e. an investment of 4 mcm/day/year starting from 2010. Therefore, the maximum investment parameter of the non-NAM, non-import resource operators is increased from a total of 2 mcm/d/y of production capacity to 6 mcm/d/y starting from 2010. It should be noted that this implies biogas can be produced at costs comparable to those of natural gas production. As this is currently not yet the case, this would have to be achieved by granting a subsidy to biogas producers.

In summary, the assumptions underlying this scenario are the stabilization of average demand, an increase in demand volatility and the commencement of large scale biogas production.

Figure 7.1 shows the consequences for the development of H-gas demand over time. Average demand remains constant, but volatility increases. In the top graph, volatility is based on average demand. In the bottom graph, volatility is based on actual demand. It can be seen that volatility in the D-average scenario is substantially larger than in the base scenario, whereas volatility in the D-actual scenario is in turn larger than in the D-average scenario. The blue and green tips in the first seven and final six years of the simulation also signify that demand and contracted supply are not always covered by the supply delivered. This happens most often in the D-actual scenario.

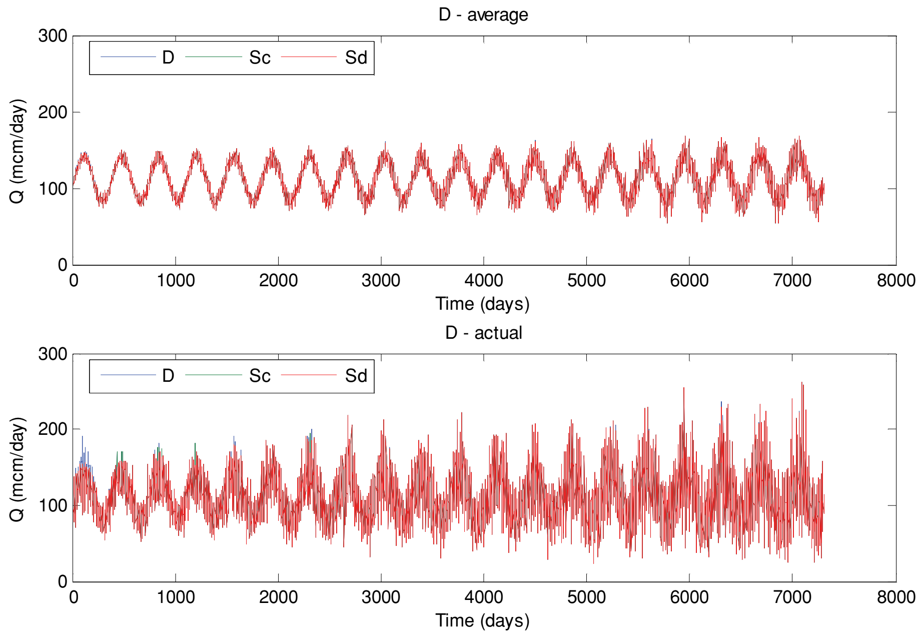


Figure 7.1: Supply and demand for H-gas in the transition scenario.

Figure 7.2 shows the corresponding system integrities and buffer volumes for H-gas and G-gas. In the D-average scenario, system integrity is maintained throughout the simulation and buffer volumes are at their maximum continuously. This means the system is able to accommodate the increase in demand volatility. However, in the D-actual scenario some problems occur. In the early years of the simulation, the higher volatility results in an intensified use of the buffer and in some breaches of system integrity for both H-gas and G-gas.

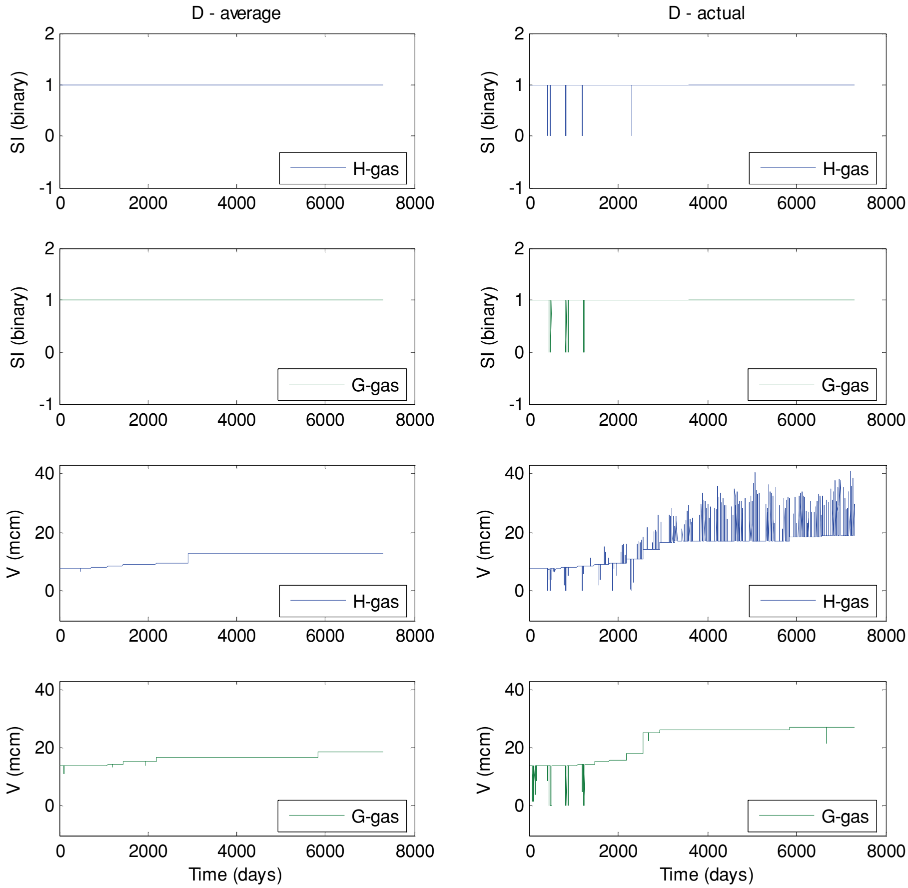


Figure 7.2: System integrity and buffer volumes in the transition scenario.

An additional consequence is a recurring oversupply of H-gas in later years, surfacing in the buffer. Although the model is not programmed to show a breach of system integrity when the buffer volume is too high, there could well be serious consequences to such an event. This oversupply is caused by a combination of import inflexibility, an increase in downward volatility of demand and the traders' storage strategies.

Traders are programmed to use their storages on the basis of the 'peak shaver' principle, which means they aim to have their storages filled throughout the year. Therefore, when inflexible import is high and demand is low, the residual supply of gas cannot be stored. This could be remedied by replacing the 'peak shaver' principle with the 'volume shifter' principle. In accordance with this principle, traders would empty their storages in winter to allow the import surplus to be injected and stored in summer.

Figure 7.3 shows the effects on prices for both scenarios. End-user prices are higher than in the base scenario, and higher in the D-actual scenario than in the D-average scenario. As the contract quantity for end-users depends on their maximum daily consumption, their capacity costs are positively correlated with demand volatility. In the D-average scenario, the spot price is lower on average but more volatile than in the base scenario. After the first few years, only a few isolated and short-lived price spikes occur. The results for the D-actual scenario display the same trend more strongly. Spot prices are now continuously below the oil index, with the exception of year one, but their volatility has increased further. Both these trends can be explained by the increase in demand volatility. The increase in user demand volatility translates into an increase in the volatility of the bids and offers made by traders on the spot market. It follows that the spot price is more volatile too.

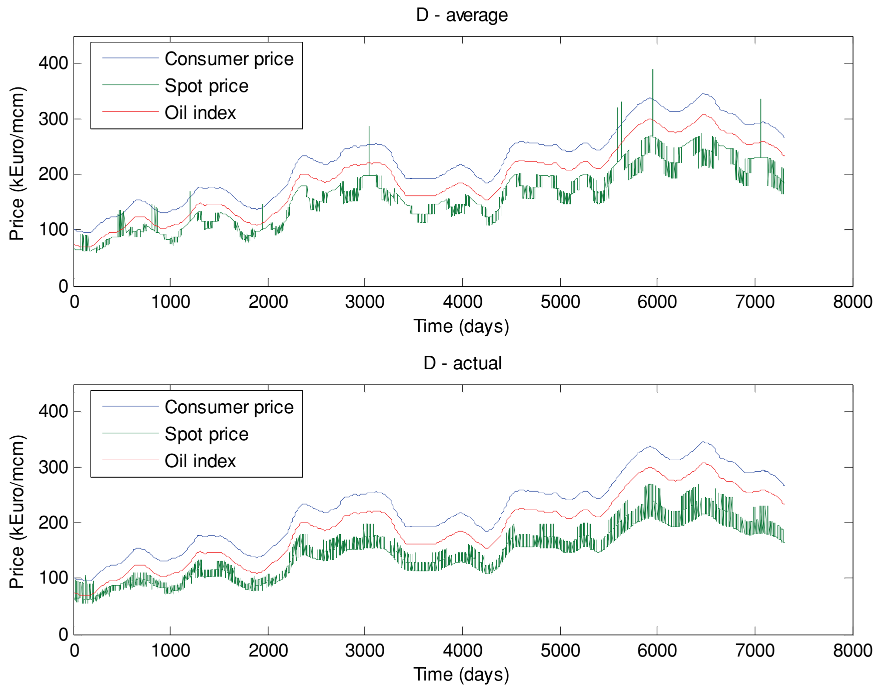


Figure 7.3: Prices in the transition scenario.

The absence of price peaks, producing a lower average spot price, can be explained as follows. In the base scenario, price peaks were caused by traders which were short on supplies because of an increase in market share or declining indigenous production. In the transition scenarios, the decline in indigenous production is counteracted by the production of biogas. The changes in market share are similar, but their effect is also dampened. The extra flexibility purchased by traders to cope with the increase in demand volatility is also used to deal with increases in market share. Therefore, when demand volatility increases, the impact of increases in market share will become smaller to the point where they no longer cause price peaks on the spot market.

Finally, the supply and demand for contracts is shown in Figure 7.4. They provide an illustration of the large amount of additional capacity that is needed when volatility increases. Whereas the lines are still relatively smooth in the D-average scenario, the lines have become highly irregular in the D-actual scenario. It can also be seen that in the D-average scenario, trader offers are continuously above user requests, but in the D-actual scenario, user requests sometimes exceed trader offers, as it has become more difficult for traders to forecast demand accurately.

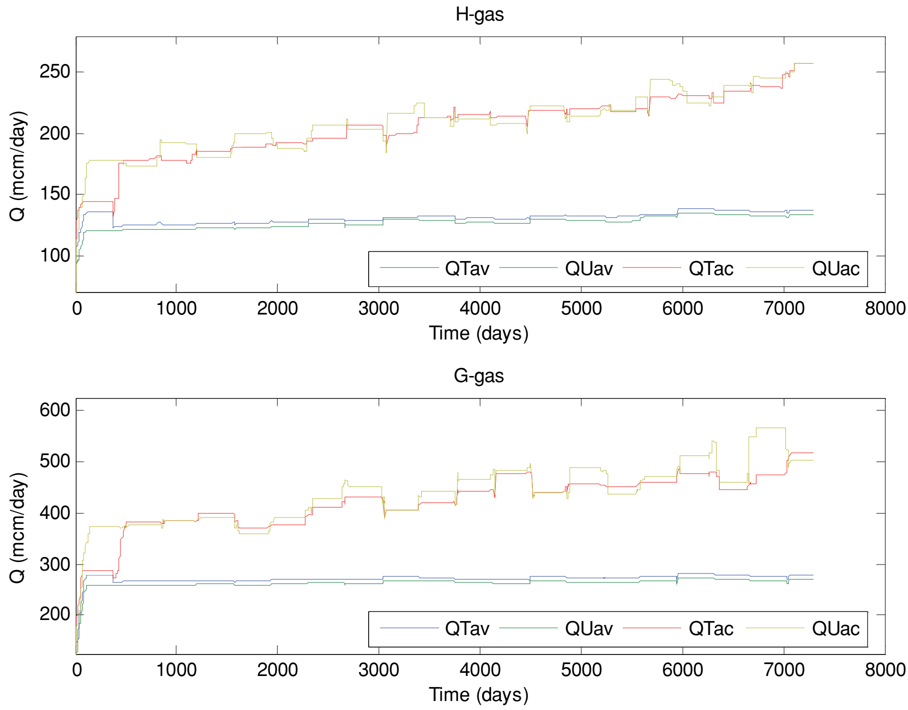


Figure 7.4: Supply and demand for contracts in the transition scenario.

Results for both transition scenarios are summarized in Table 7.1. As described above, end-user prices increase, spot prices are lower on average but more volatile, and the oil index is the same as in the base scenario. This means the price condition is met less often for end-users, more often for spot prices and just as often for the oil index. In the D-average scenario, the quantity condition is not met slightly more often than in the base scenario, and the physical condition is still met continuously. In the D-actual scenario, security conditions deteriorate severely, as the quantity condition is not met for longer periods, and the physical condition is also not met for a number of days.

Table 7.1: Performance indicators for the transition scenarios.

			D-average	D-actual
Average price:	End-user	=	225.8 kE/mcm	241.4 kE/mcm
	Spot	=	160.2 kE/mcm (volatility: 11.2 kE/mcm)	145.7 kE/mcm (volatility: 14.1 kE/mcm)
	Oil-indexed	=	191.2 kE/mcm	191.2 kE/mcm
Quantity condition not met:	H-gas	=	15 out of 7300 days	126 out of 7300 days
	G-gas	=	3 out of 7300 days	120 out of 7300 days
Physical condition not met:	H-gas	=	0 out of 7300 days	10 out of 7300 days
	G-gas	=	0 out of 7300 days	23 out of 7300 days
Price condition not met:	End-user	=	1211 out of 7300 days	1702 out of 7300 days
	Spot	=	5 out of 7300 days	0 out of 7300 days
	Oil-indexed	=	166 out of 7300 days	166 out of 7300 days

It can be concluded that the implementation of the transition to a more sustainable energy system can have positive as well as negative effects on the functioning of the natural gas market. Which of these will be dominant depends on their relative magnitude and warrants careful examination. In the D-average scenario, stable average demand and increased domestic production counterbalance the increase in volatility. The results from this scenario imply that the transition to a sustainable energy system can proceed with minimal damage to affordability and supply security. However, in the D-actual scenario, the volatility in demand becomes such that affordability and supply security are reduced significantly. It is notable that the decrease in affordability is permanent, whereas the decrease in supply security is temporary. After the initial disturbance, the system readjusts itself and reaches a new equilibrium. This implies that the changes incorporated in the transition scenario cause a decrease in affordability, the magnitude of which depends on the values of the parameters. In addition, when the changes are large enough and progress fast enough, supply security decreases as well, but is eventually restored.

7.3 Internationalization scenario

As outlined in Section 6.2, the principle of the gas roundabout is to make the Netherlands an attractive location for transhipment by providing the necessary physical infrastructure and accompanying services. These consist of sufficient transport capacity, blending capacity, interconnections with neighboring grids, access to underground storages and LNG-terminals, and a liquid trading hub. If the Netherlands succeeds in becoming such an international hub, it means demand for these services will to a large extent decouple from domestic consumption. In such a case, the Dutch market will have to adjust rapidly to an increase in demand for its services.

With regard to internationalization, it is useful to distinguish:

- *Import*, which is defined as a gas flow which originates outside the Netherlands and is consumed inside the Netherlands. The decline of domestic production combined with increasing consumption will increase import.
- *Export*, which is defined as a gas flow which originates inside the Netherlands and is consumed outside the Netherlands. The increase of Dutch traders' market shares in other countries will increase export. Similarly, an increase in the market share of trading firms which are supplied by Dutch producers will increase export.
- *Transit*, which is defined as a gas flow which is both produced and consumed outside the Netherlands, but is transported through the Netherlands (and possibly stored and traded there) in between. Transit can increase because the volume of gas transported from production locations to consumption locations increases, or because existing flows change course to make use of a more attractive route (i.e. through the Netherlands).

In recent years, several studies have tried to quantify the scope for additional import, export and transit through the Netherlands. Jepma (2001) estimated that gas flows with a magnitude of 135 mcm/d in the year 2000 and with a magnitude of 200 mcm/d in the year 2010 pass the Netherlands and could potentially be rerouted through the Netherlands. In 2001 he estimated that of these flows, 12 mcm/d could potentially be rerouted immediately. Studying the same phenomenon, ECN (Lise et al., 2005) found a maximum actual rerouting of 14-78 mcm/d in 2004. Gasunie's transport outlook from 2008 to 2014 (GasTransportServices, 2007) shows an expected increase of exit capacity from 761 to 773-852 mcm/d (i.e. an increase of 12-91 mcm/d), whereas import capacity is expected to increase from its current 98 mcm/d to 132-168 mcm/d (i.e. an increase of 34-70 mcm/d). A simultaneous decrease of domestic production from 677 to 552 mcm/d (i.e. a decrease of 125 mcm/d) is expected.

All three processes play a role in the process of internationalization. The formation of a gas roundabout is characterized by a relatively rapid growth of these flows initially, due to the increased attractiveness of the Netherlands. This is followed by a new equilibrium when the potential for the additional rerouting of gas flows through the

Netherlands is exhausted. Therefore, this scenario assumes a temporary increase in the growth rate of these flows, after which normal growth resumes.

The degree of internationalization of the Dutch market is represented by adding and/or modifying the following parameters:

1. *Import capacity.* A variable is added to the physical module of the network operator, called import capacity. It represents the (entry) connection capacity of the network to other, foreign networks and/or pipelines. In previous simulations, it was assumed that import capacity was sufficient and could be safely omitted. In this scenario, however, import capacity is explicitly included as a possible limiting factor. It is treated exactly like other transport variables, which means traders purchase a quantity each year together with their transport capacity, and the network operator invests in additional capacity on the basis of trader demand. The amount of import capacity available to a trader functions as a constraint to the amount of gas it can request daily to the "Import" agent through its source selection algorithm. The network operator is assumed to anticipate the gradual shift from domestic production to import caused by the decline in domestic reserves. It therefore increases import capacity with a yearly percentage in addition to trader demand to accommodate this shift. The initial value and yearly increase of import capacity are set at 45 mcm/d and 8% p.a. respectively. Their values were calibrated by adding these two variables to the base scenario and then replicating the base scenario results.
2. *Export demand.* Increasing export and transit can both be represented by increasing the demand of the export agents. To simulate this increase, the H-gas export agent's demand is set to grow with a higher percentage from 2010 to 2015, after which its initial growth of 1.5% p.a. resumes. Three growth rates are simulated: +5%, +7.5%, and +10%. These translate into increases in average demand over a period of five years of 14.5 mcm/d, 22.0 mcm/d and 30.3 mcm/d respectively. These numbers are in the lower range of the estimates cited above, which is in line with the small initial values chosen for other transport capacity variables, as a consequence of working with daily rather than hourly time steps (see Section 6.3.3).
3. *Trader sourcing.* Internationalization requires foreign flows of gas to enter the Dutch market. The availability of such flows is already assumed in the base scenario by providing the "Import" agent with large reserves. However, it is the share of imported gas in the trader agents' portfolios which determines actual imports. In this scenario, the traders' preferences for imported gas will be increased, representing both foreign traders entering the Dutch market with their own sources of gas and Dutch traders diversifying their portfolios by including more foreign suppliers. The magnitude of this increase is set to such a level that the additional gas export is wholly sourced from the import agent. Exceptions are made for the integrated trader-resource operator agent, which still prefers gas from its own sources, and for GasTerra, which still executes small field policy. This means that, starting from an initial even

spread between import and domestic production, the share of imports in trader portfolios is increased to 53%, 55.5% and 58% respectively.

Implicitly, these increases in import, export and transit, generate an increase in the demand for transport and storage capacity, and an increase in trade. However, these are a function of trader behavior and therefore do not have to be changed directly.

In summary, the assumptions underlying this scenario are a restriction of the available import capacity, an increase in demand from the H-export agent, and an increase in the share of imported gas in trader portfolios.

Figure 7.9 shows the demand for H-gas in the three internationalization scenarios. During the first ten years, demand is equal for all three realizations. Thereafter, demand levels diverge, stabilizing at three distinct levels. The left graph shows actual daily demand, and the right graph shows the demand for contracts. In all three scenarios, contract demand is higher than supply at some point during the transition, with the highest growth scenario showing the largest and longest gap.

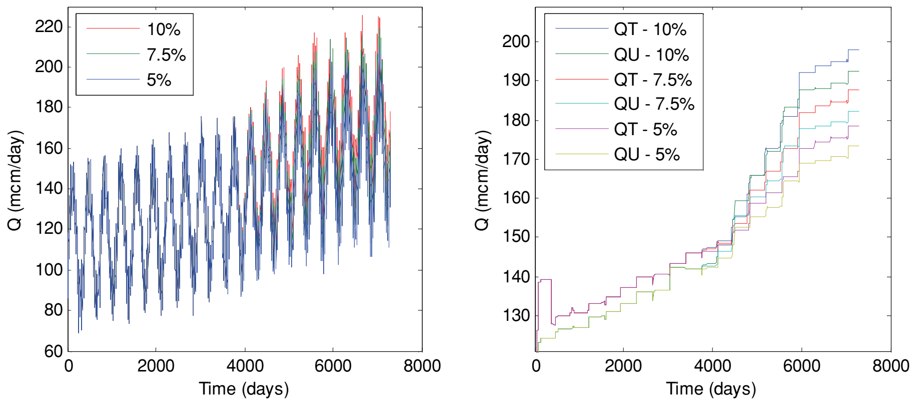


Figure 7.9: H-gas demand in the three internationalization scenarios.

Figure 7.10 shows spot prices, which start to diverge in the years of rapid growth and have not yet fully converged at the end of the simulation. The highest growth scenario produces the highest and longest price peaks, although the difference between scenarios is limited.

System integrity and buffer volumes are shown in Figure 7.11. It can be seen that, in the 5%-scenario, system integrity is maintained and the buffer volume is not required for balancing. In the 7.5%-scenario, the buffer volume is used during three winters and system integrity is breached in two of them. These breaches occur in years 17 and 18, i.e. after the period of high growth has ended. This indicates a time lag between the increase in demand and the shortage in supply occurring. In the 10%-scenario, buffer volumes are depleted and system integrity is breached in the years 16 to 20.

Compared to the 7.5%-scenario, supply security is compromised earlier in the simulation and the system has not yet adjusted itself successfully at the end of the simulation.

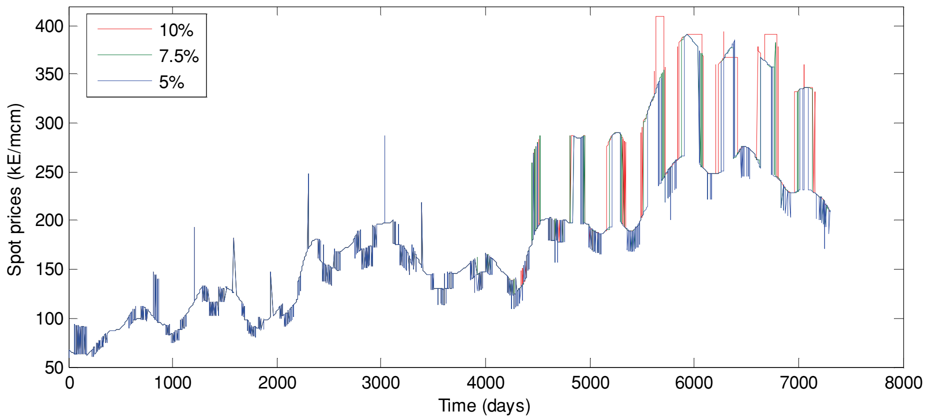


Figure 7.10: Prices in the three internationalization scenarios.

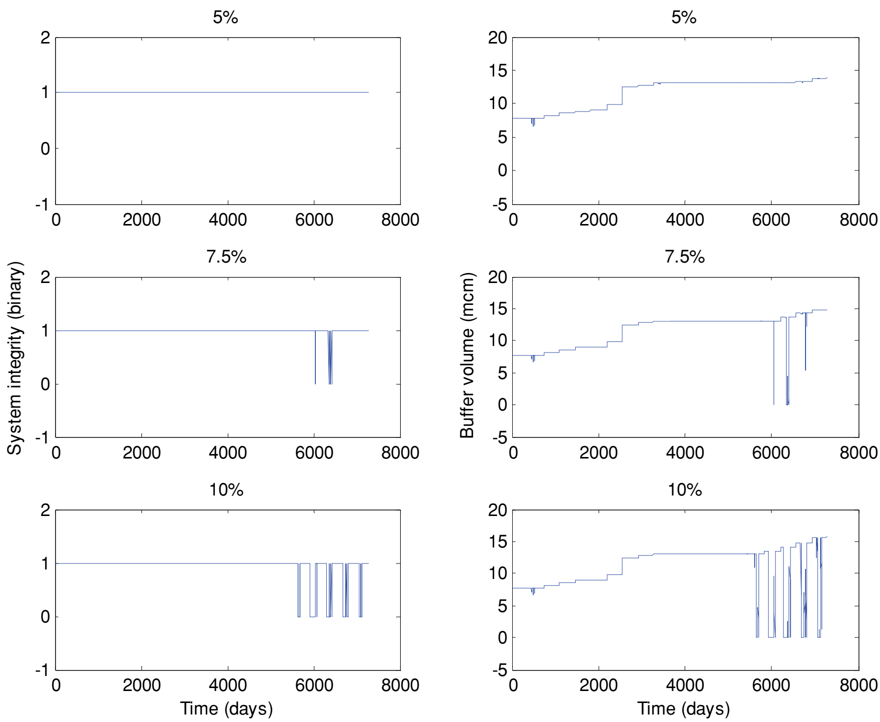


Figure 7.11: System integrity and buffer volumes in the three internationalization scenarios.

Results for the three internationalization scenarios are summarized in Table 7.2. End-user prices are almost constant. The slight decrease in price which accompanies the higher growth rate is due to the belated adjustment of contracts to demand, which causes users to pay for less capacity than they use. Spot prices increase slightly with higher growth and become a bit more volatile. Oil-indexed prices are unchanged. The quantity condition and physical condition are not met increasingly often with higher growth in the case of H-gas, whereas the results for G-gas are unchanged. Although the average price is lower, the price condition is met less often with higher growth. This is caused by the relative development of the end-user price over time, which is lower initially but ends at a higher level. The price condition results for spot and oil-indexed prices follow logically from the results presented above.

Table 7.2: Performance indicators for the three internationalization scenarios.

	Export demand:		5%	7.5%	10%	
Average price:	End-user	=	224.6	224.3	224.0	kE/mcm
	Spot	=	177.1	181.0	187.4	kE/mcm
	Spot volatility	=	11.3	12.1	12.3	kE/mcm
	Oil-indexed	=	191.2	191.2	191.2	kE/mcm
Quantity condition not met:	H-gas	=	32	65	112	out of 7300 days
	G-gas	=	2	2	2	out of 7300 days
Physical condition not met:	H-gas	=	0	51	488	out of 7300 days
	G-gas	=	0	0	0	out of 7300 days
Price condition not met:	End-user	=	1203	1207	1212	out of 7300 days
	Spot	=	544	744	984	out of 7300 days
	Oil-indexed	=	166	166	166	out of 7300 days

The cause of the time lags identified above and the general mechanics underlying these results can be clarified by looking at Figure 7.12. The three graphs on the left show the import capacity available to traders plotted against their import contracts with the "Import" agent. Initially, import capacity is greater than the sum of import contracts. However, when imports start to increase rapidly, contracts exceed the available capacity until additional investments close the gap. When growth is higher, the gap is wider and takes longer to close. During the existence of such a gap, storage is used to compensate the shortfall in imports, which is shown in the three graphs on the right.

In the 5%-scenario, storage volumes are depleted to a larger extent in the years following the rapid growth in imports. However, storages are not emptied completely and can be refilled to their maximum in summer. In the 7.5%-scenario, storages are depleted completely and cannot be filled entirely in the years a system integrity breach occurs. The same pattern is visible in the 10%-scenario, but lasts for a longer period.

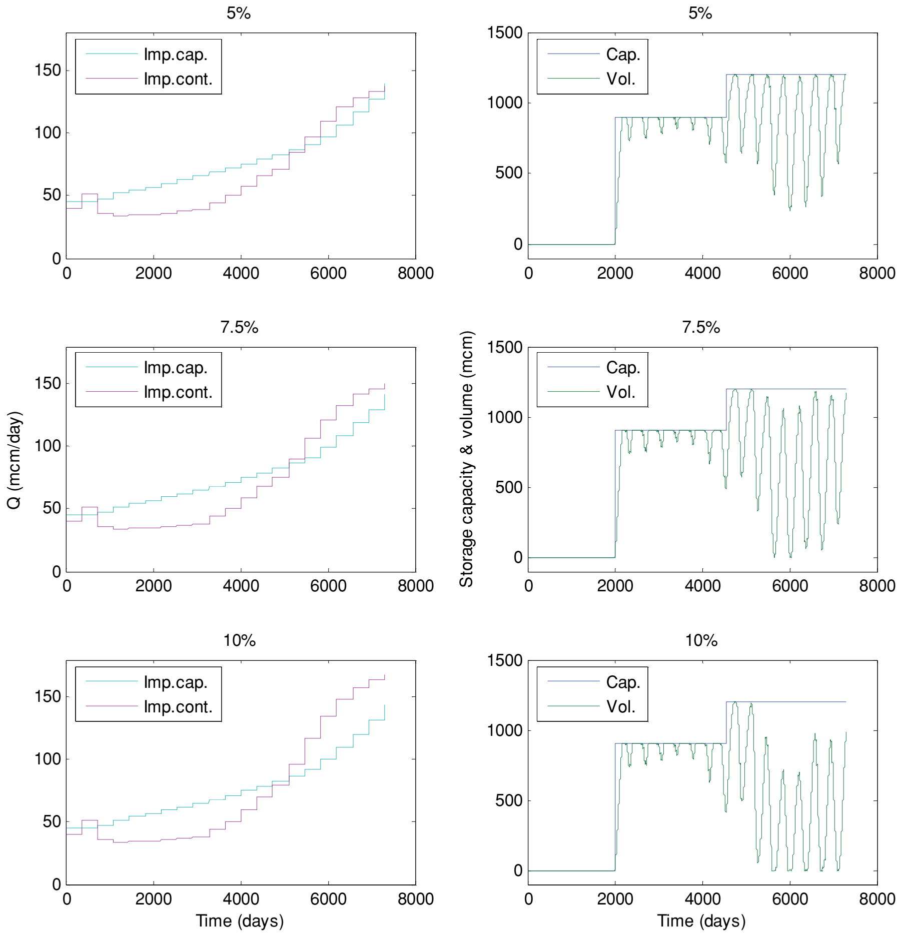


Figure 7.12: Import and storage in the three internationalization scenarios.

It can be concluded that, in this scenario structure, the process of internationalization can pose risks to security if it proceeds rapidly. The process also affects spot prices by making them higher on average and more volatile. These results depend on two main factors, which are the process of investment in import capacity and the allocation mechanism of the capacity available. With regard to the first, it could be argued that the network operator will invest the optimal amount of capacity if its expectations are correct. It should however be remembered that the Dutch regulator judges investments in transport capacity with regard to the criterion of cost minimization for consumers. It is therefore probable that actual investment will be on the low side of the expectation range. With regard to the second factor, the model assumes that capacity is re-allocated each year. The current dual system of open seasons for additional capacity and short term contracts for existing capacity in the Netherlands can prevent this by allowing companies to book capacity several years ahead of time. This provides companies with certainty about the future availability of capacity, allowing them to adjust their planning. The drawback is that companies will not be able to book capacity at short notice when unexpected opportunities arise, thus creating a tradeoff between stability and flexibility as discussed in Section 5.7.

7.4 Responsivity scenario

The third scenario focuses on the effect a new institutional environment can have on market parties. Before liberalization, utilities were monopolists owned by the local government. By and large, the post-liberalization traders are private parties with a focus on profit instead of public service. Therefore, leaving the parameters and algorithms from the pre-liberalization model unchanged may not be realistic. This scenario delves into the possible changes in behavior as a consequence of the new institutional setup. The focus in this scenario will be on the traders, excluding GasTerra, who are most affected by the drive towards competition.

The responsivity of companies and individuals to market signals is represented by modifying the following parameters:

1. *Contracting safety margins*. The contracting safety margins determine the demand for and supply of storage, transport, production and supply contracts. When safety margins are high, buyers buy a bit more than they expect to use, and sellers supply a bit less than they expect to have available. In other words, low safety margins make a market more efficient, but also increase the risk of a mismatch between supply and demand. Economic theory dictates that profit maximizing companies will, when the expected value of a variable is normally distributed, use the most likely outcome for their calculations, as this will on average yield the profit maximizing solution. Although in this case the expected value of variables is not necessarily normally distributed, it would seem a good first order approximation to trader behavior in a liberalized market. In this scenario, the traders' safety margins are therefore reduced to 1, which means they are effectively absent.
2. *Sources of flexibility*. In the base scenario, traders fulfilled their need for flexibility by contracting storage capacity and signing flexible supply contracts with GasTerra. However, the GasnetNL2-model provides a third source of flexibility: the spot market. Ecorys (Rademaekers and Van Gorp, 2007) also made this observation in a study of the Dutch seasonal flexibility market. It said that the TTF is on the verge of turning into a reasonable alternative for storage or contractual swing. In this scenario, traders therefore divide their flexibility demand equally between these three sources.
3. *Storage strategy*. In the base scenario, stored gas is saved until the trader needs it to balance its own supply and demand. However, traders can also choose to sell their stored gas at a profit on the spot market when there is demand for it. In other words, the spot market algorithm can be adjusted to take into

account the possibility of selling gas from a storage facility. In the winter of 2005, the British government launched an inquiry into the causes of the high spot prices on the UK market, and specifically, why gas from storages on the continent was not being delivered to the UK market. The reply of the storage owners was that they were saving their stored gas for later in winter (personal correspondence of the author). The choice between these two strategies can be conveniently represented in the spot market strategy of traders, which can choose to include their storage production capacity in their spot offer. This has the upside of possibly making higher profits on the spot market at the cost of facing a risk with regard to one's own needs later in winter. In this scenario, the algorithm is modified so that traders will sell their stored gas on the spot market when the spot price is sufficiently high.

In summary, this scenario assumes a change in the behavior of traders in three respects. Their contracting safety margins are reduced, they rely on the spot market for a share of their flexibility requirements, and they utilize their storage capacity in a higher-risk, more profit-oriented way.

Figure 7.13 shows the system integrity and buffer volumes resulting from this scenario. It is clear that, although initially the changes cause no trouble, some problems start to surface in the second part of the simulation. Buffer volumes sink dangerously low in four consecutive years, resulting in a breach of system integrity four times. Thereafter, the system readjusts itself and no further problems occur until the end of the simulation.

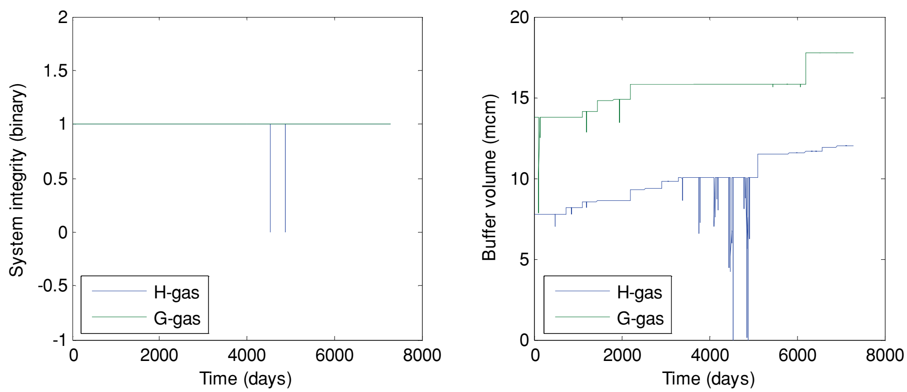


Figure 7.13: system integrity and buffer volumes in the responsivity scenario.

Figure 7.14 shows the development of prices over time, as well as the penalties charged to traders. The spot price has become yet more volatile than in previous scenarios, and is also higher on average. Although some small penalties are incurred by traders throughout the simulation, the peaks coincide with the depletion of the buffer volumes.

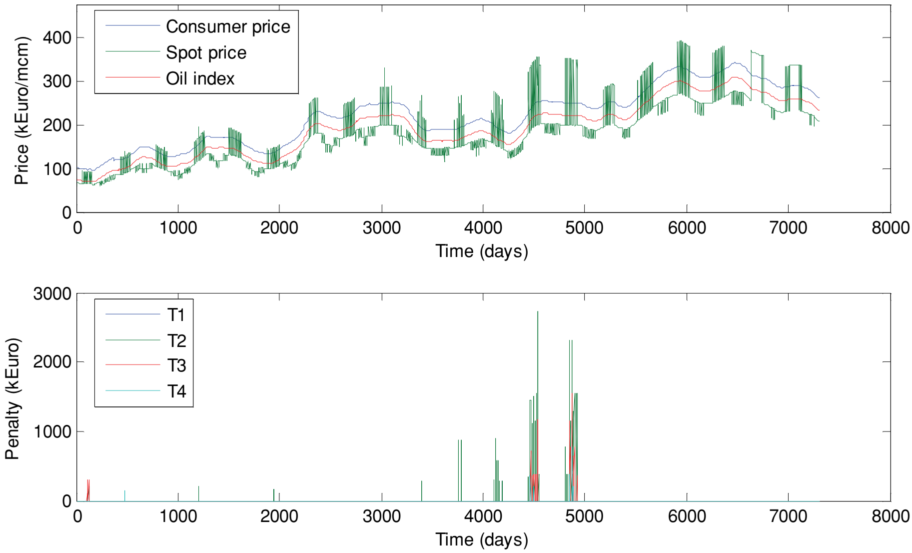


Figure 7.14: Prices and penalties in the responsivity scenario.

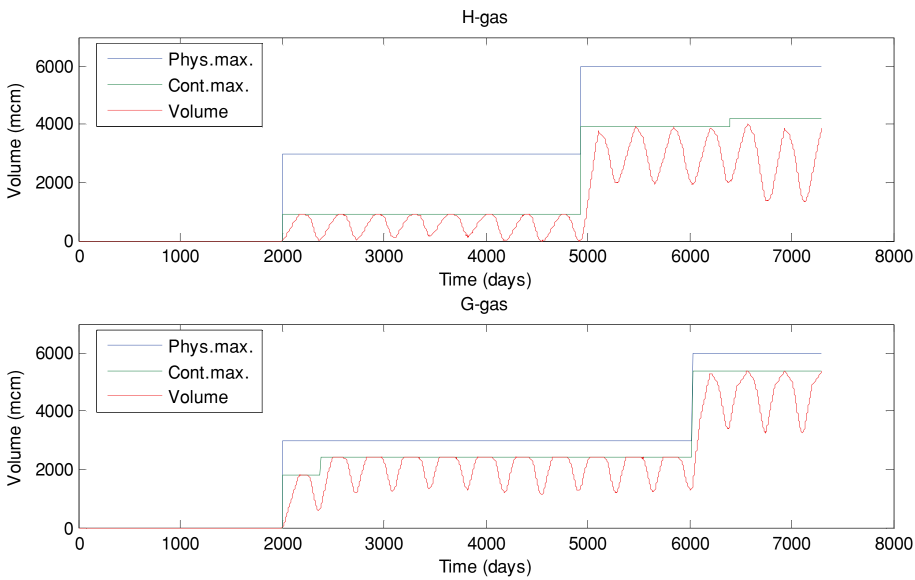


Figure 7.15: Storage volumes in the responsivity scenario.

Figure 7.15 shows the development of stored volumes over time. Compared to the base scenario, less storage capacity is rented throughout the simulation. However, the available capacity is used more intensively. H-gas storages are emptied before the end of winter on several occasions.

Finally, Figure 7.16 shows the fraction of users under contract by each trader and the spot quantities traded among traders. The left graph indicates that the integrated user-trader (T1) and the independent trader (T2) gain market share at the expense of the other traders. They are able to do so because they do not have production facilities integrated into their companies. This allows them to decrease the amount of flexibility purchased to a level below that of the other traders, which receive most of their flexibility from their own production facilities.

The spot quantities traded are in line with this result. The traders which have economized on their flexibility are forced to buy gas on the spot market at a high price from the traders which have their own production facilities. GasTerra (T3) plays an especially crucial role in this respect. The graph shows its spot sales decrease over time, until they are almost reduced to zero. At that moment, buffer volumes start to be depleted. Only when a storage facility from the NAM is taken into use, is there enough capacity to satisfy the demand of traders T1 and T2.

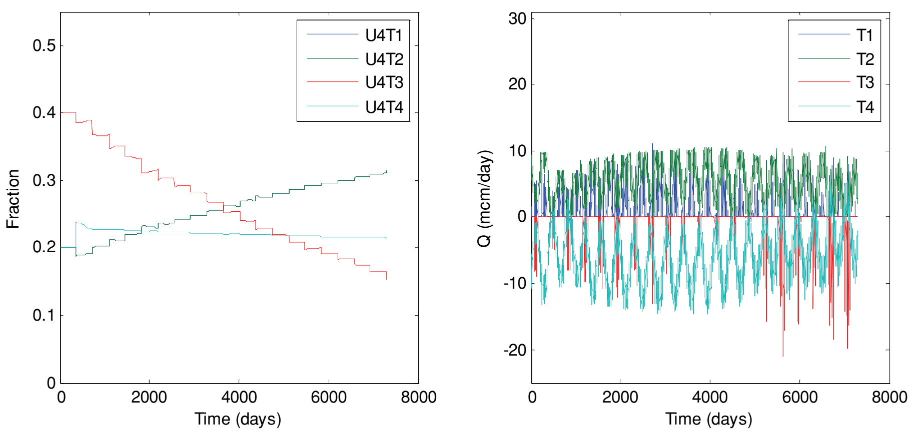


Figure 7.16: Contract changes and spot quantities traded in the responsivity scenario.

Results for the responsivity scenario are summarized in Table 7.3. The average end-user price has decreased compared to the base scenario, which is a product of the lower safety margins and flexibility costs. As explained above, the spot price is higher and more volatile. The oil-indexed price is unchanged. Results for the quantity condition are the same as in the base scenario, as the changes made to trader behavior do not affect the contracting process between users and traders. The physical condition for H-gas is not met for five days, whereas the physical condition for G-gas is unaffected. As a consequence of the price changes, the price condition is met more often for the end-user price and met less often for the spot price.

Table 7.3: Performance indicators for the responsivity scenario.

Average price:	End-user	=	218 kE/mcm
	Spot	=	180 kE/mcm (volatility: 31.0 kE/mcm)
	Oil-indexed	=	191 kE/mcm
Quantity condition not met:	H-gas	=	12 out of 7300 days
	G-gas	=	2 out of 7300 days
Physical condition not met:	H-gas	=	5 out of 7300 days
	G-gas	=	0 out of 7300 days
Price condition not met:	End-user	=	1130 out of 7300 days
	Spot	=	502 out of 7300 days
	Oil-indexed	=	166 out of 7300 days

It can be concluded from this scenario that the behavior of traders can prove pivotal to the functioning of the system as a whole. Competition between traders creates an incentive for them to seek cost reductions. More specifically, when traders reduce costs by reducing safety margins, contracting less flexibility and adopting a different storage strategy, they can gain market share at the expense of other traders. This has a positive effect on affordability. At the same time, however, supply security is reduced. The traders' strategy to minimize unused capacity and to rely on the spot market leaves them exposed to sudden shortages. Therefore, the success of their strategy depends on the availability of excess supply from other parties. In this scenario, such supplies were available initially, because of an excess of production capacity. This excess gradually faded away because of declining indigenous production, after which system integrity was breached. Investment in a storage facility by the NAM then created a new source of overcapacity, due to its size. The continuation of this process results in cyclical system behavior where under- and overcapacity alternate and security is threatened periodically.

7.5 Conclusions from the scenario analysis

In this chapter, the ENETSIM methodology was applied once more to perform a study of the Dutch natural gas market. The post-liberalization structure was analyzed by subjecting it to three scenario studies. These scenarios highlighted some of the challenges awaiting the Dutch market in the coming years.

First, the transition scenario showed the different effects of a transition to a more sustainable energy system. As such a transition causes the average volume of demand to stabilize, the risk of insufficient supply and resulting price peaks become less pressing. Instead, the increased volatility of demand requires additional supply flexibility. This reduces affordability and may reduce security if the adjustment proceeds too slowly.

Second, the internationalization scenario investigated the effects of increases in import, export and transit. As the single European market is a highly complex system, the magnitude of these flows is rather unpredictable, and the market's response to such flows may therefore lag behind. In particular, import capacity can become scarce and prevent market parties from accessing the supplies they need. Results show no long term effect on affordability, but do show a reduction in security in case of a high and/or fast growth in international gas flows.

Third, the responsivity scenario further explored the possible behavior of traders facing competitive pressures in the market. The scenario corroborates the observations made in the base scenario that increased risk taking by traders can destabilize the system. Their efforts to gain market share by cutting costs increase affordability, but tend to erode the buffers present in the system and thereby reduce security.

In general, this chapter has drawn attention to the impact of shifts in long term trends on policy goals. Of the three scenarios constructed in this chapter, one has a positive effect on affordability, one a negative effect and one is neutral. In each case, the effect was instantaneous and permanent. The spot price showed a separate development, mainly reflecting the short term supply and demand position. With regard to security, effects manifested themselves differently. Each scenario reveals a possible threat to security, but in two cases this threat is temporary, and in the third it occurs intermittently. Furthermore, these threats to security often take some time to materialize.

Expectations proved crucial in this context. When the present is very similar to the past, the behavior of actor agents is well attuned to their environment. However, when circumstances change rapidly, changes in behavior often lag behind. In the case of rational expectations, all shifts are foreseen and behavior is adjusted timely. In the more realistic case of adaptive expectations, however, there is a transition period in which behavior and the resulting contracts and physical infrastructures are inadequate, giving rise to security risks and price peaks.

It can be concluded that developments of the kind investigated in this chapter can affect both affordability and security. While effects on affordability are largely time-independent and unavoidable, effects on supply security depend on the rate at which changes take place. This underlines the need for a dynamic, out-of-equilibrium analysis of such developments, as well as the need for careful attention to timing issues from a policy perspective.

The next chapter will conclude this thesis by summarizing the main results of the study, drawing some general conclusions, and outlining some possibilities for the further development of ENETSIM.

8. Summary, conclusions and outlook

8.1 Summary of the preceding chapters

This chapter starts with a summary of the previous chapters, after which some conclusions are drawn and an outlook on the further development of the ENETSIM framework is provided.

In Chapter 1, this study began with a short overview of energy policy. The three objectives of energy policy, affordability, security and sustainability, were identified and the possibility of tradeoffs between objectives was discussed. It was argued that, due to the division of labor, the most practical way to coordinate policy goals is to provide policy makers aiming for a single objective with optimization constraints. Next, natural gas policy was introduced as a part of energy policy. It was concluded that, as sustainability cannot be achieved on the level of natural gas policy, the key tradeoff in structuring the natural gas market is that between affordability and security. The concept of hierarchical optimization was then introduced to clarify the role of regulatory authorities in structuring the market after liberalization. This led to the statement of the study's objective and the formulation of five research questions. These were:

1. How can the concepts of supply security and affordability be usefully defined?
2. What should a modeling framework for analyzing the natural gas market with regard to these concepts look like?
3. What general conclusions can be drawn on the basis of this framework?
4. What is the effect of liberalization on the Dutch natural gas market?
5. What are the possible effects of current trends unfolding in the Dutch natural gas market?

Finally, an outline of the study was provided.

Chapter 2 continued the study by introducing the natural gas value chain, consisting of seven processes: exploration, production, processing, transport, storage, distribution and consumption. Using the value chain, liberalization was defined as a change in the way the value chain was organized, with as its three pillars competition and TPA, unbundling, and a new role for governments. Next, the concept of affordability was explored further, and it was compared to the related concepts of competitiveness and economic efficiency. It was concluded that affordability was the most useful concept for policy to focus on. Finally, the concept of supply security was examined. First, it was explained why it is especially relevant to natural gas markets. Second, a quantitative definition was provided in the form of three conditions which have to be fulfilled for supply to be considered secure. Finally, security risks were divided into internal risks, following from the structure of the economic system, and external risks, originating outside of the economic system.

With these concepts defined, attention was turned to modeling the natural gas market in Chapter 3. First, a survey of existing models was performed. It was concluded that most models used to analyze the market as a whole are based on a single set of modeling principles, denoted as market equilibrium modeling. These models were found to have the drawback that they necessarily assume complete supply security. Therefore, dynamic system modeling was introduced as an alternative. The chapter continued with a more detailed identification of the characteristics required. To this end, a three dimensional modeling space was constructed, consisting of the market imperfections, model scope and model granularity dimensions. Existing models were then assigned a place in modeling space. On the basis of this classification, the minimum requirements and the optimal structure of the models to be developed were identified. The strategy adopted was to include all market imperfections from the beginning, and then to gradually increase model scope and granularity.

Chapter 4 consisted of a general description of the ENETSIM framework. ENETSIM is an application of agent-based computational economics. It contains five actor agents, splitting the value chain into five parts: exploration and production, transport, storage, trade and consumption. These agents can be connected to each other through three institutional agents, corresponding to the three governance structures identified in transaction cost economics: markets, contracts and hierarchies. Therefore, the basis of each ENETSIM model is an agent network. The model is a dynamic system proceeding in discrete, single day time steps. Each day, information, gas and money flows between agents. Each year, contracts are renegotiated and investments in infrastructure can be made. Model output consists of actor level output from individual agents and system level output concerning the functioning of the system as a whole with regard to affordability and supply security.

Next, each of the agents and their decision algorithms were described in more detail. For the user agent, these are demand generation and contracting. For the trader agent, these are spot market trading, source selection and contracting. For the resource operator agent, these are production, investment and contracting. For the storage operator agent, these are operation, investment and contracting. For the network operator agent, these are balancing, investment and contracting. The integration agent does not contain any decision algorithms of its own, but instead modifies the existing algorithms of individual agents. The contract agent contains an algorithm for bargaining and the spot market contains a market clearing algorithm. The dataset required for a model to be operational was then described, and finally, some options for the verification and validation of ENETSIM models were provided. A combination of input validation and sensitivity analyses was chosen to test the framework's validity.

The ENETSIM methodology was first applied in Chapter 5. An elementary model consisting of a user agent, a contract agent and a resource operator agent was developed and its implications were explored. In addition, a procedure for testing the system's robustness against external shocks was outlined and some sample results were shown. In the following sections, the elementary model was gradually expanded. First, it was expanded with a trader and a contract, introducing a middleman between consumer and producer. One of the contracts was then replaced with an integration agent, showing how the altered network functioned. Thereafter, competition was introduced by constructing an agent network consisting of two resource operators, two traders and a spot market. The competition for market share and the possibility of trading on the spot market showed the risks created by imperfect information. Two further models were developed in which the network operator and storage operator were added to the agent network.

Finally, all previous models were combined into a single network covering the whole value chain and satisfying the minimum requirements for a model identified in Chapter 3. In addition, a modification of this model was described which enabled the use of the model in an educational game. It was also explained that using ENETSIM to play such games could be a way to engage in iterative participatory modeling, which is a promising method for model development and validation. Chapter 5 ended with some general conclusions about the ENETSIM methodology, thereby answering the second sub-question. It was concluded that ENETSIM can be used to analyze the affordability and supply security associated with a given market structure, that combining both in one model enables the identification of tradeoffs, and that the framework is of sufficient generality to incorporate a wide range of phenomena derived from empirical observation rather than computability requirements.

The next two chapters focused on the performance of the Dutch market. The history of the Dutch market and Dutch energy policy were described briefly, after which two studies of the Dutch market were performed. In Chapter 6, the effect of liberalization on the Dutch natural gas market was analyzed. Two models were developed to this end. One corresponded to the market structure before liberalization and the other to the structure of the market after liberalization. The dataset was identical where possible to facilitate the comparison of both agent networks. First the agent network, decision algorithms and dataset of the pre-liberalization model were described. The results showed how affordability was mainly a function of the oil price, whereas security was a function of the Gasunie's contracting safety margin. A sensitivity analysis was performed for this contracting safety margin, which revealed a tradeoff between security and the NAM's profits.

Next, the post-liberalization model's agent network, decision algorithms and dataset were described. The results from the post-liberalization model showed some potential for an increase in affordability, although this hinged on upstream price competition developing, which was becoming increasingly unlikely due to the depletion and concentration of reserves. The security of the system was found to have become a function of many different market parties' behavior and, in particular, of their willingness to take risk. In the case of storage operators and network operators, an increased willingness to take investment risk translated into a higher security, whereas an increase in the willingness of traders to take risk lowered security.

The results from both models were then used to draw some conclusions about the effect of liberalization on affordability and supply security. It was concluded that unbundling created a risk of imperfect coordination between different parts of the value chain and increased risks with regard to investment and contracting. Competition created additional uncertainty but also the potential for price decreases. The changed role of government meant that the objectives of market parties could no longer be equated to governmental objectives. Instead, government now has to impose constraints on market parties to influence their actions.

A third and final application of the ENETSIM framework followed in Chapter 7. Three scenarios for the future of the Dutch market were designed on the basis of the main uncertainties currently facing the Netherlands. They were implemented by adjusting the decision algorithms and dataset of the post-liberalization model. The first scenario to be examined was called "transition". It was concerned with the transition to a sustainable energy system. The adjustments made to the business as usual scenario were a stabilization of the average demand for gas, an increase in the volatility of demand and partial substitution of natural gas by biogas. It was concluded that this transition would reduce affordability and, depending on the volatility of demand, could also reduce security.

The second scenario was called "internationalization", and was concerned with the integration of the Dutch market with neighboring markets, thereby increasing import, export and transit. This was modeled by adding the variable "import capacity", increasing demand for export and increasing the traders' preferences for imports at the cost of domestic supplies. It was concluded that internationalization, while leaving affordability largely unaffected, could reduce security if the speed and magnitude of the process were sufficient.

The third scenario implemented was called "responsivity", and examined the possible change in behavior of traders as a function of the liberalized market environment. These behavioral changes were implemented by adjusting trader behavior in three ways: reduced safety margins, partial reliance on the spot market for flexibility, and a higher risk use of storage. Results showed that the collective change in behavior improved affordability but reduced security. In general, it was concluded that these shifts occurring in the market could jeopardize its stability because of the time it takes market parties to react to these shifts and find the optimal response.

8.2 General conclusions

Having recalled the main results and conclusions from each chapter, some general conclusions can now be drawn regarding this study as a whole. Keeping in mind the study's objective, this section subsequently addresses three topics: the development of a modeling framework to support policy making, the design of natural gas policy, and the impact of current developments in the natural gas market on policy goals.

On the basis of a literature survey, it was concluded that there is currently a lack of tools to support policy making for the natural gas market. This study has begun to fill that gap by developing the ENETSIM modeling framework. The main contributions of ENETSIM to natural gas market modeling are the following. First, the basis of the framework is a two-level characterization of the natural gas market, with a top level where policy decisions are made and a bottom-level where companies act within the confines of the legal constraints formulated at the top level. Their combined behavior then translates into system performance at the top level. This hierarchical structure ensures that policy making is always linked to system performance indirectly, via the behavior of individual companies. It enables a detailed analysis of the effect of the motives and strategies of individual companies on system performance and the possibilities of influencing these results through policy making.

Second, the concept of natural gas market performance has been extended to encompass both affordability and supply security. By doing so, the framework reveals tradeoffs between these policy goals which remain hidden when they are treated separately. Third, the framework incorporates out-of-equilibrium dynamics, again revealing properties of the natural gas market which remain hidden in an equilibrium analysis. Security issues in particular have proven to be time-dependent, out-of-equilibrium phenomena. Finally, the framework is structured in such a way that a broad range of additions can be incorporated in a straightforward manner, which facilitates its further development.

The application of this framework has yielded a number of recommendations with regard to policy design. First, policy makers pursuing one of the goals of energy policy should seriously consider the possible effects of their policies on other goals. While the acknowledgement that the pursuit of one goal should not proceed at the cost of another is a useful starting point, it is by no means enough. Tradeoffs are inevitable, and they are more widespread than is generally assumed. Therefore, a more integrated form of policy design would be preferable, where each policy is tested for its effect on all policy goals instead of focusing on a single goal.

Second, the reliance on traditional economic models for policy making introduces a policy bias in favor of affordability at the cost of security. Policy makers should take account of the fact that high supply security is not a property of the free market, but of the models describing it. Third, the natural gas market post-liberalization has become a complex, non-linear system in which seemingly small changes can have large effects. Therefore, it has become crucial for policy makers to build up expertise with regard to the dynamics of this system and take such effects into account in policy development. This is equally valid for individual companies active in the market, whose performance also depends on their understanding of the market's dynamics.

Finally, a number of conclusions can be drawn with regard to the impact of more specific developments on the performance of the natural gas market. Liberalization comprises both a change in market structure and a new method for optimizing this structure. The new market structure offers some scope for improvement in affordability, but also introduces some risks to security. Furthermore, steering the market through regulation rather than through participation is a highly complex process that is not yet well understood.

The more recent trends identified in the transition, internationalization and responsivity scenarios yield some additional observations. Each development involves some tradeoff between policy goals. The transition to a sustainable energy system furthers sustainability at the cost of affordability and supply security; internationalization creates business opportunity at the risk of reduced security; and responsivity improves affordability at the cost of supply security. While such tradeoffs are unavoidable and may be defensible, there is much to be gained from a careful implementation of such changes. While effects on affordability and sustainability are relatively straightforward, effects on supply security often depend on the rate and magnitude of change in a system. Therefore, adverse effects on supply security can be mitigated to some extent by adequate planning and management of these developments.

8.3 Further development of ENETSIM

Having drawn conclusions on the basis of the results obtained so far, the study ends with some thoughts on the further development of ENETSIM. Although the framework in its current state has proven useful, a number of changes and additions can still be made to improve upon it. A logical place to start would be to improve the existing models by fine-tuning their behavioral algorithms and the dataset. However, this section takes a longer term perspective and looks at the possibilities of improving the fundamentals of the framework. A non-exhaustive list of such additions is provided below.

In general, three kinds of development are envisaged. The first is to transform conditions exogenously imposed on a model into endogenous factors; in other words, turning input into output. Some ideas are presented for endogenizing the shape of the agent network and endogenizing the behavior of agents. The second is to incorporate empirically observed phenomena in the framework which are as of yet missing. Three instances of these are discussed: mergers and acquisitions, more detailed physical infrastructure and the development of a term market. The third is to widen the scope of analysis by including the sustainability objective.

The first candidate for endogenous representation is the agent network. A drawback of the current setup is that agents cannot extend their business to or retreat from other parts of the value chain. The extension of business into other segments, particularly, has received a stimulus from liberalization (Eikeland, 2007). This omission can be remedied by designing a 'generalized agent' which consists of all five actor agents subsumed under a single integration agent. Any number of such generalized agents could be included in a model. Differences between agents would then consist solely of the data provided to them. Such data would then consist of their initial presence in different parts of the value chain, where a value of zero would imply absence and thus functionally reduce these agents to simpler ones. An additional class of decision algorithms could then govern the choice to extend or discontinue business in other parts of the value chain. Such generalized agents would interact with each other through contract and market agents where applicable. Figure 8.1 shows an example of such a generalized agent network.

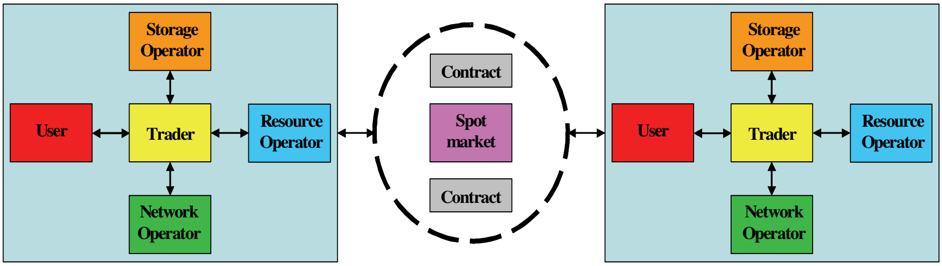


Figure 8.1: A generalized agent network.

The behavior of agents could also be endogenized. A highly active research subfield within agent-based computational economics is the topic of learning in agents. A survey of work done so far was performed by Brenner (2006), and a first application to the natural gas market was developed by Tchung-Ming (2007). Introducing learning in the behavior of agents would mean that, instead of assigning one decision algorithm to them from the start, multiple algorithms could be supplied, after which the agent could adapt them and/or switch between them during the simulation on the basis of current information.

Furthermore, the framework can be extended by introducing some additional phenomena. An extension related to making the agent network dynamic, is the introduction of mergers and acquisitions. Mergers and acquisitions have become an increasingly important part of the natural gas market after liberalization, to the point where virtually all large energy companies are involved in them (Verde, 2008). By increasing concentration, these activities reduce competition and may significantly affect policy goals (Thomas, 2003). Modeling an acquisition would entail the reduction of values in one agent combined with the simultaneous increase of the same value in another agent. For example, if one trader acquires another, the value of variables in the acquired agent (supply contracts, production contracts, etc) would be reduced to zero, while at the same time the values of the same variables in the acquiring agent would be increased by the same amount. The decision to merge or acquire would again be governed by an additional set of decision algorithms.

A second extension could be made by providing the physical modules of the resource operator, network operator and storage operator with some more detailed functionality. In other words, the framework could be moved further along the granularity axis in modeling space. Some more variety could be introduced in the physical characteristics of reservoirs, rather than using a single template. The transport network could be assigned spatial characteristics rather than a single magnitude. Finally, different types of storage facility (small or large, rapid response peak shavers or slow response volume shifters) are already available, but the choice between them made by storage operators and/or traders could be endogenized.

A final useful extension is to extend the spot market agent's functionality with a term market, turning it into a fully fledged market agent. This would entail the introduction of trade in new products. In addition to trading gas to be consumed the next day, gas could be traded for the next month, the next quarter, or the next year. This would make the market a more complete alternative for bilateral contracting and may therefore add important new dynamics to models.

The third option for further development is to widen the scope of analysis by incorporating the sustainability objective. This can be done by first identifying useful indicators for sustainability, e.g. the amount of CO_2 emitted or the rate of resource depletion. Next, these indicators must be added to the framework as model output. As ENETSIM already contains the physical processes determining sustainability, model fundamentals are unaffected. A similar procedure can be followed for additional objectives if so desired. The optimization problem can then be reformulated as maximizing affordability (or minimizing consumer price) under the dual constraint of a degree of supply security and a degree of sustainability. Alternatively, sustainability can be maximized under the constraints of affordability and supply security.

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Appendix I: reservoir pressure calculation

--- Matlab code ---

```
Initialization
          statevar1 = volume at time t
          statevar2 = pressure at time t

Calculation
          volfrac = statevar1 / initial volume
          Pmax = initial pressure
          T = reservoir temperature
          P_cp = 4.600.000;
          T_cp = 191;
          P_r = Pmax / P_cp;
          T_r = T / T_cp;
          p = P_r;
          t = T_r;
          a = 1.39 * (t - 0.92) ^ 0.5 - 0.36 * t - 0.101;
          b = (0.62 - 0.23*t) * p + (0.066 / (t-0.86) - 0.037) * p * p + 0.32 / 10 ^ (9 * (t
- 1)) * p ^ 6.0;
          c = 0.132 - 0.32 * log10(t);
          d = 10 ^ (0.3106 - 0.49 * t + 0.1824 * t * t);
          Z = a + (1 - a) / exp(b) + c * p ^ d;
          PmaxZ = Pmax / Z;
          PZ = PmaxZ - (PmaxZ / initial volume) * (1 - volfrac) * initial volume
          Pfunc = @(x)PZ * (a+(1-a)/exp((0.62 - 0.23*t) * (x/P_cp) + (0.066 / (t-0.86)
- 0.037) *          (x/P_cp) * (x/P_cp) + 0.32 / 10 ^ (9 * (t - 1)) * (x/P_cp) ^ 6.0) +
c*(x/P_cp)^d) - x;
          P = fzero(Pfunc,statevar2);
          Pab = abandonment pressure
          if        Pab >= P
                    prodcap = 0;
          else
                    deltaPprod = P - (well flow pressure * P);
                    T_sc = 287;
                    P_sc = 100000;
                    Z = P / PZ;
                    E = (P / P_sc) * (T_sc / T) * (1 / Z);
                    prodcap = deltaPprod * productivity index * E;
          end
end
```

Appendix II: ENETSIM datasets

Gasnet1:

Name	Value
Capmargin	0.2
CP	[325 150 15]
Expfactors	[3 3]
Oilindexedprice	150
Prospect	[3000 4e+007 0.25 4e+006 313 7.5e-010 1]
Rcosts	75
Rcsm	0.98
Rinvcosts	10000
Rinvmargin	1.1
Rlead	1
Rmaxinv	30
Rmoneyinit	0
Rres1	[2e+006 2.5e+006 4e+007 0.25 4e+006 313 8e-008 400]
Runtime	1825
Tempav	9.75
Tempdev	7.25
Ucsm	1.02
Udamage	200
Udemand	[14 250]
Uincome	48000
Umoneyinit	0
Coldwinter	0
Interruption	[200 210 1]

Gasnet2:

Name	Value
Capmargin	0.2
Expfactors	[3 3]
Oilindexedprice	150
Prospect	[3000 4e+007 0.25 4e+006 313 7.5e-010 1]
Rcosts	75
Rcsm	0.98
Rinvcosts	10000
Rinvmargin	1.1
Rlead	1
Rmaxinv	30
Rmoneyinit	0
Rres1	[2e+006 2.5e+006 4e+007 0.25 4e+006 313 8e-008 400]
Runtime	1825
Tcapmargin	1.05
TCfixed	100
Tcommargin	1.05
Tcsm	1.02
Tempav	9.75
Tempdev	7.25
Tmoneyinit	0
TR	[325 150 15]
Ucsm	1.02
Udamage	200
Udemand	[14 250]
Uincome	48000
Umoneyinit	0
UT	[325 157.5 15.75]
Coldwinter	0
Interruption	[200 210 1]

Gasnet3:

Name	Value
Coldwinter	0
Capprice	10
Expfactors	[3 3]
Interruption	[900 910 0.6]
Oilindexedprice	150
Prospect	[3000 4e+007 0.25 4e+006 313 7.5e-010 1]
Rcosts	75
Rcsm	0.98
Rinvcosts	10000
Rinvmargin	1.1
Rlead	1
Rmaxinv	40
Rmoneyinit	0
Rres1	[2e+006 2.5e+006 4e+007 0.25 4e+006 313 8e-008 400]
Runtime	1825
Tcapmargin	1.01
TCfixed	100
Tcommargin	1.01
Tempav	9.75
Tempdev	7.25
Tmoneyinit	0
Ucsm	1.02
Udamage	300
Udemand	[14 250]
Uincome	48000
Umoneyinit	0
UT	[325 151.5 10.1]

Gasnet4:

Name	Value
Coldwinter	0
Capmargin	0.2
Expfactors	[3 3]
Interruption	[900 910 1]
Oilindexedprice	150
Prospect	[3000 4e+007 0.25 4e+006 313 7.5e-010 1]
R1res1	[1.4e+006 2.5e+006 4e+007 0.25 4e+006 313 8e-008 200]
R2res1	[1.4e+006 2.5e+006 4e+007 0.25 4e+006 313 8e-008 200]
Rcosts	[75 75]
Rcsm	[0.98 0.98]
Rinvcosts	10000
Rinvmargin	[1.1 1.1]
Rlead	1
Rmaxinv	[0 8]
Rmoneyinit	[0 0]
Runtime	1825
T1spot	[0.8 0.75 1.2]
T2R2	[163 150 15]
T2spot	[1.1 0.9 1.25]
Tcapmargin	[1 1.05]
TCfixed	[100 100]
Tcommargin	[1 1.05]
Tcsm	[1 1.25]
Tempav	9.75
Tempdev	7.25
Tmoneyinit	[0 0]
Ucsm	1.02
Udamage	200
Udemand	[14;250]
Uincome	48000
Umoneyinit	0
UT1	[163 150 15]
UT2	[163 157.5 15.75]
UTfrac	[0.5 0.5]

Gasnet5:

Name	Value
BNT	[7 150 15]
Capmargin	0.2
Expfactors	[3 3]
Interruption	[900 910 1]
Nbufmargin	0.02
Ncosts	3
Ngrexp	1.02
Nintegcosts	10000
Ninvcosts	1500
Nlead	1
Nmargin	1.05
Nmoneyinit	0
Ntranscap	350
Oilindexedprice	150
Penprice	300
Prospect	[3000 4e+007 0.25 4e+006 313 7.5e-010 1]
Rabfactor	1500
Rcosts	75
Rcsm	0.98
Rinvcosts	10000
Rinvmargin	1.1
Rlead	1
Rmaxinv	40
Rmoneyinit	0
Rres1	[2e+006 2.5e+006 4e+007 0.25 4e+006 313 8e-008 400]
Runtime	1825
Tcapmargin	1.05
TCfixed	100
Tcommargin	1.05

Gasnet6:

Name	Value
Capmargin	0.2
Expfactors	[3 3]
Interruption	[900 910 1]
Oilindexedprice	150
Penprice	300
Prospect	[3000 4e+007 0.25 4e+006 313 7.5e-010 1]
Rcosts	75
Rcsm	0.98
Rinvcosts	10000
Rinvmargin	1.1
Rlead	1
Rmaxinv	0
Rmoneyinit	0
Rres1	[2.5e+006 2.5e+006 4e+007 0.25 4e+006 313 8e-008 340]
Runtime	1825
Sbpers	5
Sbundle	[7 1 200]
Scosts	200
Sgrexp	1
Sinvcosts	150000
Slead	5
Smargin	1.15
Smoneyinit	0
Sres1	[1000 6000 2.2e+007 3.2e+007 1.1e+007 313 2.3e-008 3e-009 35 5]
Sthresh	3
Tcapmargin	1.05
TCfixed	100
Tcommargin	1.05
Tcsm	1.02

Gasnet6b:

Name	Value
Coldwinter	0
Capmargin	0.2
Expfactors	[3 3]
Interruption	[900 910 1]
Oilindexedprice	150
Penprice	300
Prospect	[3000 4e+007 0.25 4e+006 313 7.5e-010 1]
Rcosts	75
Rcsm	0.98
Rinvcosts	10000
Rinvmargin	1.1
Rlead	1
Rmaxinv	0
Rmoneyinit	0
Rres1	[2.5e+006 2.5e+006 4e+007 0.25 4e+006 313 8e-008 340]
Runtime	1825
Sbpers	5
Sbundle	[7 3.5 800]
Scosts	200
Sgrexp	1
Sinvcosts	150000
Slead	1
Smargin	1.15
Smoneyinit	0
Sres1	[4000 30000 3.4e+007 3.6e+007 2e+007 313 1.73e-008 1.73e-008 35 17.5]
Sthresh	3
Tcapmargin	1.05
TCfixed	100
Tcommargin	1.05
Tcsm	1.02
Tempav	9.75
Tempdev	7.25
Tmoneyinit	0
TR	[333 150 15]
TS	[3 46]
TScsm	1.02
Ucsm	1.02
Udamage	300
Udemand	[14 250]
Uincome	48000
Umoneyinit	0
UT	[350 157.5 17.75]

GasnetNL1:

Name	Value
Convfac	3
Dbufcap	6
Dbufmargin	0.05
Dcosts	2.5
Dcsm	1.05
Dintegcosts	10000
Dinvcosts	1500
Dlead	1
Dmoneyinit	0
Dtranscap	120
Expfactors	[3 3]
GR1	[40 1 1 1 10]
GR2	[47.5 1 1 1 10]
GR3G	[170 2 0 1 10]
GR3H	[35 2 0 1 10]
Interruption	[900 910 1]
LG	[105 1.05 13.5]
Lmoneyinit	0
Nbufcap	[7.75 13.75]
Nbufmargin	[0.05 0.05]
Ncosts	[2.5 2.5 2.5]
Ncsm	1.05
Nintegcosts	10000
Ninvcosts	1500
Nlead	1
Nmargin	1.05
Nmoneyinit	0
Ntranscap	[155 275 50]
Oilindexedprice	75
Oilprice	25
Prospect	[3000 4e+007 0.25 4e+006 313 7.5e-010 1]
R1res1	[2e+006 2.5e+006 4e+007 0.25 4e+006 313 8e-008 200]
R2res1	[500000 1e+006 4e+007 0.25 4e+006 313 8e-008 50]
R3res1	[1.4e+006 2.9e+006 3e+007 0.25 4e+006 313 2e-006 340]
R3res2	[400000 800000 4e+007 0.25 4e+006 313 8e-008 70]
Rcapmargin	[0.1 0.1 0.1 0.2]
Rcosts	[100 100 100 50]
Rcsm	0.95
Rdecline	[0.98 0.98]

Rinvcosts	10000
Rinvmargin	[1 1.1 1.15]
Rlead	1
Rmaxinv	[0 2 2]
Rmoneyinit	0
Runtime	7300
S1bundle	[50 20 3000]
S1res1	[3000 25000 3.2e+007 3.5e+007 2.4e+007 313 4e-008 1.35e-008 50 20]
S1res2	[3000 25000 3.2e+007 3.5e+007 2.4e+007 313 4e-008 1.35e-008 50 20]
Sbpers	1
Scosts	400
Sinvcosts	100000
Slead	5
Smargin	1
Sthresh	1
Tcapmargin	1.05
TCfixed	[100 50]
Tcommargin	1.05
Tcsm	1.05
Tempav	9.75
Tempdev	7.25
Tmoneyinit	0
TSG	[0 0 0 0 0 0 400]
TSH	[0 0 0 0 0 0 400]
U1demand	[2.5 27]
U1L	[50 1.1 17.5]
U2demand	[3 33]
U2L	[60 1.1 17.5]
U3demand	[9 80]
U3G	[150 1.05 13.5]
U4demand	[1.5 43]
U4G	[60 1.05 13.5]
U5demand	[1 26]
U5G	[40 1.05 13.5]
U6demand	[1.5 43]
U6G	[60 1.05 13.5]
Ucsm	[1.02 1.02 1.02 1.02 1.02 1.02]
Udamage	[300 300 300 300 300 300]
Ugrowth	[1.00004 1.00004 1.00004]
Uincome	[8100 9900 24000 12900 7800 12900]
Umoneyinit	[0 0 0 0 0 0]
Coldwinter	0

GasnetNL2:

Name	Value
BNT	[7.75 13.75 1 15]
Convfac	3
Expfactors	[3 3]
Interruption	[900 910 1]
Nbufcap	[7.75 13.75]
Nbufmargin	[0.05 0.05]
Ncosts	[2.5 2.5 2.5]
Ncsm	1.05
Nintegcosts	10000
Ninvcosts	1500
Nlead	1
Nmargin	1.05
Nmoneyinit	0
Ntranscap	[155 275 50]
Oilindexedprice	75
Oilprice	25
Penmargin	1.1
Prospect	[3000 4e+007 0.25 4e+006 313 7.5e-010 1]
R1res1	[2e+006 2.5e+006 4e+007 0.25 4e+006 313 8e-008 200]
R2res1	[250000 500000 4e+007 0.25 4e+006 313 4e-008 25]
R3res1	[1.4e+006 2.9e+006 3e+007 0.25 4e+006 313 2e-006 340]
R3res2	[400000 800000 4e+007 0.25 4e+006 313 8e-008 70]
R4res1	[250000 500000 4e+007 0.25 4e+006 313 4e-008 25]
Rabfactor	1500
Rcapmargin	[0.1 0.1 0.1 0.2 0.095]
Rcosts	[100 100 100 50 100]
Rcsm	[0.95 0.95 0.95 0.95]
Rdecline	[0.98 0.98 0.98]
Rinvcosts	10000
Rinvmargin	[1 1.1 1.15 1.1]
Rlead	1
Rmaxinv	[0 1 2 1]
Rmoneyinit	0

Runtime	7300
S1bundle	[50 20 3000]
S1res1	[3000 25000 3.2e+007 3.5e+007 2.4e+007 313 4e-008 1.35e-008 50 20]
S1res2	[3000 25000 3.2e+007 3.5e+007 2.4e+007 313 4e-008 1.35e-008 50 20]
S2bundle	[5 2 300]
S2res1	[3000 25000 3.2e+007 3.5e+007 2.4e+007 313 4e-008 1.35e-008 50 20]
S2res2	[3000 25000 3.2e+007 3.5e+007 2.4e+007 313 4e-008 1.35e-008 50 20]
Sbpers	[1 10]
Scosts	[400 400]
Sinvcosts	100000
Slead	5
Smargin	[1 1.15]
Smoneyinit	0
Sthresh	[1 0]
T1N	[5 0 0]
T1R1	[5 1 1 1 10]
T1SG	[0 0 0 0 0 0 46]
T1SH	[0 0 0 0 0 0 46]
T1spot	[1.2 0.8 1.5]
T1T3G	[35 1.5 0 1 15]
T1T3H	[30 1.5 0 1 15]
T2N	[5 0 0]
T2R1	[5 1 1 1 10]
T2SG	[0 0 0 0 0 0 46]
T2SH	[0 0 0 0 0 0 46]
T2spot	[1.1 0.9 1.6]
T2T3G	[35 1.5 0 1 15]
T2T3H	[10 1.5 0 1 15]
T3N	[120 250 50]
T3R1	[30 1 1 1 10]
T3R2	[25 1 1 1 10]
T3R3G	[170 2 0 1 10]
T3R3H	[35 2 0 1 10]
T3SG	[0 0 0 0 0 0 400]

T3SH	[0 0 0 0 0 0 400]
T3spot	[1.3 0 0]
T4N	[25 0 0]
T4R1	[0 1 1 1 10]
T4SG	[0 0 0 0 0 0 46]
T4SH	[0 0 0 0 0 0 46]
T4spot	[0.7 0.6 1.4]
Tcapmargin	1.05
TCfixed	[100 100 50 50]
Tcommargin	1.05
Tcsm	1.05
Tempav	9.75
Tempdev	7.25
Tmoneyinit	[0 0 0 0]
U1demand	[2.5 27]
U1T	[25 25 0 0]
U2demand	[3 33]
U2T	[30 30 0 0]
U3demand	[9 80]
U3T	[0 0 150 0]
U4demand	[1.5 43]
U4T	[12 12 24 12]
U5demand	[0.1 4]
U5T	[2 2 2 2]
U6demand	[1.5 43]
U6T	[12 12 24 12]
U7demand	[0.9;22]
U7int	0.25
Ucsm	[1.02 1.02 1.02 1.02 1.02 1.02]
Udamage	[300 300 300 300 300 300 300]
Ugrowth	[1.00004 1.00004 1.00004 1.00004]
Uincome	[8100 9900 24000 12900 1200 12900 6600]
Umoneyinit	[0 0 0 0 0 0 0]
Coldwinter	0

Appendix III: Handouts for an educational game

Handout 1: Human Storage Operator

You are a storage operator active in the gas market. Your goal is to maximize your cash flow over the next five years. Currently you own one storage facility which you rent out for use by traders. You have the option to invest in up to four additional storage facilities with identical characteristics. With increasing demand, and the incumbent's resource base declining, demand for storage is expected to increase.

1. General information:

Last year, average gas demand was 90 mcm/day, with a seasonal swing of 30%. Industry expectations are that average demand will increase with 3%/year. The oil-indexed gas price is currently at 150 kE/mcm and is expected to increase with about 3%/year. The incumbent's resource base is expected to decline, which means there is potential for new storage operators and resource operators to enter the market. Plans have been launched for additional storage facilities and increased exploration activity, but it remains to be seen whether these plans will materialize.

N.B.: Expectations may be inaccurate!

2. Personal information:

- The specifications of your existing facility are:
  Working Volume = 1000 mcm,
  Production Capacity = 35 mcm/day,
  Injection Capacity = 7.5 mcm/day.
- The capacity of the existing facility is sold in 5 bundles, each containing 1/5 of capacity.
- You can invest in up to 4 new facilities, each physically identical to the existing one. The investment costs for new facilities are incorporated in the operating costs. Therefore, operating new facilities is more expensive than operating your existing facility.
- Your shareholders demand a return on capital of at least 15%, but if you make excessive profits (over 30%) the regulatory authority will intervene.
- Your storages can be used by both the human trader and the computer trader. At the start of the game, both traders have a contract for 2 bundles, at a price of 30 kE / bundle / day, due to expire in 6 months.

3. Daily Cash Flow:

M (t) = M (t-1) + (P * B) - Coe - Con

With:

M (t)	=	Money stock at time t
M (t-1)	=	Money stock at time t-1
P	=	Price per bundle
B	=	# Bundles sold
Coe	=	Operating costs of existing facility (= 100 kE / facility / day)
Con	=	Operating costs of new facility (= 200 kE / facility / day)

4. Decisions:

- Choose the timing of your investment in each additional storage facility (if you choose not to invest, write 'x'):

  N.B.: a storage year starts halfway the gas year.

Facility	Year of investment
1	
2	
3	
4	

- Choose the markup over your operating costs each year:

  N.B.: a storage year starts halfway the gas year.

Year	Markup (%)
1	
2	
3	
4	
5	

Handout 2: Human Network Operator

You are the national transport network operator. You have a legal obligation to provide sufficient transport capacity at a reasonable price. In addition, you need sufficient means of balancing the network (i.e. input = output) when traders fail to do so by themselves. Finally, you also need to run a profitable business, so don't buy and/or build more than you need!

1. General information:
Last year, average gas demand was 90 mcm/day, with a seasonal swing of 30%. Industry expectations are that average demand will increase with 3%/year. The oil-indexed gas price is currently at 150 kE/mcm and is expected to increase with about 3%/year. The incumbent's resource base is expected to decline, which means there is potential for new storage operators and resource operators to enter the market. Plans have been launched for additional storage facilities and increased exploration activity, but it remains to be seen whether these plans will materialize.

N.B.: Expectations may be inaccurate!

2. Personal information:

- Last year, your available transport capacity was 160 mcm/day, of which 110 mcm/day was rented out to the incumbent, 20 mcm/day was rented out to the human producer and 28 mcm/day rented out to the traders using a storage facility (at that time one facility was in operation with a production capacity of 35 mcm/day).
- You can invest in additional transport capacity at the start of each year.
- Assume there is no lead time.
- All shippers rent capacity for one year.
- Take account of the fact that the transport capacity wanted by shippers may be higher than consumer demand for gas. The reason for this is that traders require some flexibility in choosing gas sources. Therefore, the maximum amount of transport capacity requested will be equal to the sum of all production capacity, both from storage operators and resource operators. If the capacity available is smaller than the amount requested, it is rationed pro rata among shippers.
- When shippers supply an insufficient amount of gas to the network, you will have to balance supply and demand using your buffer. The incumbent offers buffer capacity at a price of 10 kE / mcm / day. The gas you buy for buffering is indexed to the oil price. You are allowed to fine traders an amount equal to 1,2 times the spot price of gas / mcm for any unbalance they cause.
- The price you can charge for your transport capacity is regulated. It consists of a markup over your asset base. The regulated markup is 6% on an annual basis. Your asset base is equal to your transport capacity * 1000 kE.

3. Daily Cash flow:

M (t) = M (t-1) + Fc + (Pcap * Qcap) - Co - Ci - D - B + P

With:

M (t)	=	Money stock at time t
M (t-1)	=	Money stock at time t-1
Fc	=	Connection fee paid by consumers. (= 90 kE / day)
Pcap	=	Price of transport capacity (= asset base * regulated markup / 365 / total capacity)
Qcap	=	Quantity of transport capacity sold
Co	=	Operating costs (= 2 kE / mcm transport capacity installed / day)
Ci	=	Investment costs (= 1000 kE/mcm, to be paid once on the day of investment)
D	=	Damage incurred when system integrity is breached (= 10000 kE/day)
B	=	Cost of buffer capacity
P	=	Income from penalties administered to traders for unbalances in their portfolios

4. Decisions:

- Choose the amount of transport capacity you want to build each year in mcm/day:

Year	Transport capacity
1	
2	
3	
4	
5	

- Choose the desired amount of buffer capacity you want to rent each year in mcm/day:

Year	Buffer capacity
1	
2	
3	
4	
5	

Handout 3: Human Trader

You are one of the two suppliers to natural gas consumers. Your goal is to maximize your cash flow over the next five years. You have negotiated a long term supply contract with the incumbent, but this does not cover your needs entirely. Therefore, you have to decide how much storage capacity you want to buy, you have to develop a strategy concerning the spot market and decide on the price you want to charge consumers.

1. General information:

Last year, average gas demand was 90 mcm/day, with a seasonal swing of 30%. Industry expectations are that average demand will increase with 3%/year. The oil-indexed gas price is currently at 150 kE/mcm and is expected to increase with about 3%/year. The incumbent's resource base is expected to decline, which means there is potential for new storage operators and resource operators to enter the market. Plans have been launched for additional storage facilities and increased exploration activity, but it remains to be seen whether these plans will materialize.

N.B.: Expectations may be inaccurate!

2. Personal information:

- Currently, 50% of all consumers are your customer. If the price you charge is below/above the price charged by your competitor, your market share will increase/decrease.
- Your long term contract with the incumbent allows you to demand up to 48 mcm/day.
- Currently, 5 storage bundles are available on the market. Extra capacity is expected to become available in the course of the coming five years, with a maximum of 20 extra bundles. However, other traders may also want to buy storage bundles. One storage bundle consists of 7 mcm/day production capacity, 200 mcm storage capacity, and 1.5 mcm/day injection capacity. At the start of the simulation, you have a contract of 2 bundles for 30 kE / bundle / day, due to expire in 6 months.
- An amount of transport capacity equal to your contracted storage capacity will automatically be requested to the network operator.
- Your selling price is determined by a markup to the oil-indexed gas price.
- You can buy an amount of gas from the spot market each day, depending on the amount producers offer. Again, other traders may also want to buy gas, in which case the gas goes to the highest bidder.
- If the demand of your consumers exceeds the amount you supply, you will have to pay an unbalance penalty to the network operator.

3. Daily Cash Flow:

$$M(t) = M(t-1) + (P_{sale} * Q_{sale}) - (P_{buy} * Q_{buy}) - C_{cap} - S - T - P - F$$

With:

$M(t)$	=	Money stock at time t
$M(t-1)$	=	Money stock at time t-1
P_{sale}	=	Oil-indexed gas price * markup
Q_{sale}	=	Quantity of gas sold
P_{buy}	=	Oil-indexed gas price
Q_{buy}	=	Quantity of gas bought
C_{cap}	=	Capacity costs included in your long term contract (48 * 4 kE/day)
S	=	# Storage bundles * bundle price (bundle price is set by the storage operator)
T	=	Amount of transport capacity bought * transport price (= capacity * 2,9 kE / mcm / day)
P	=	Unbalance penalty = Spot price * markup of 20%
F	=	Fixed costs (= 100 kE / day)

4. Decisions:

- Choose the number of storage bundles you require each year:

Year	# bundles
1	
2	
3	
4	
5	

- Choose your markup over the oil-indexed gas price determining consumer price:

Markup (%)

- Choose the maximum price at which you want to purchase spot gas and the minimum price at which you want to sell excess gas. "Base load" refers to gas bought *instead of* gas from the incumbent. "Peak load" refers to gas bought *in addition to* gas from the incumbent.

Minimum selling price (% of oil-indexed price)	
Maximum base load purchasing price (% of oil-indexed price)	
Maximum peak load purchasing price (% of oil-indexed price)	

Handout 4: Human Trader-Resource Operator

You are a new entrant to the Dutch gas market. You own one producing field which is in decline. Your goal is to maximize your cash flow over the next five years. You hope to exploit the gap between rising demand and the decline of both your own and the incumbent's producing fields. You do so by exploring the subsurface for new fields and by selling gas from existing and future fields on the spot market at an attractive price.

1. General information:

Last year, average gas demand was 90 mcm/day, with a seasonal swing of 30%. Industry expectations are that average demand will increase with 3%/year. The oil-indexed gas price is currently at 150 kE/mcm and is expected to increase with about 3%/year. The incumbent's resource base is expected to decline, which means there is potential for new storage operators and resource operators to enter the market. Plans have been launched for additional storage facilities and increased exploration activity, but it remains to be seen whether these plans will materialize.

N.B.: Expectations may be inaccurate!

2. Personal information:

- The expected production curve of your existing field is attached.

- Each year, you can explore the subsurface for new fields. Your exploration effort E is a measure for the magnitude of your exploration activity. The maximum feasible value for E is 7.5. The production capacity of your new fields in (mcm/day) resulting from exploration is equal to E, but with an uncertainty margin of 30%, representing your imperfect knowledge of the subsurface. In addition, new fields have a linear production build-up period of one year.

  EXAMPLE: you choose E=5 in year one. This will result in new fields with a maximum production capacity of between 3.5 and 6.5 mcm/day. The fields will come on stream at the start of year two, and will be at full capacity at the start of year three.

- You sell your gas on the spot market. Each day you offer an amount of gas at the spot market equal to your production capacity. If the spot price is equal to or higher than your minimum selling price, you sell the amount demanded at the spot price, if it is lower you don't sell any gas that day.

- To be able to sell your gas on the spot market, you first have to transport it there. Therefore, you reserve an amount of transport capacity equal to your production capacity each year.

3. Daily Cash flow:

M (t) = M (t-1) + (P * Q) - Co - (Ce * E) - T

With:

M (t)	=	Money stock at time t
M (t-1)	=	Money stock at time t-1
P	=	Price of gas sold
Q	=	Quantity of gas sold
Co	=	Operating costs (= 120 kE / mcm production capacity installed / day)
Ce	=	Exploration costs (= 40 kE / day)
E	=	Exploration effort
T	=	Amount of transport capacity bought * transport price (= capacity * 2,9 kE / mcm / day)

4. Decisions:

- Choose your exploration effort each year:

Year	Exploration effort
1	
2	
3	
4	
5	

- Choose the minimum price at which you offer your gas on the spot market as a fraction of the oil-indexed gas price:

Minimum selling price (%)

Summary

Natural gas is a naturally occurring mix of hydrocarbons consisting primarily of methane. It is one of society's main sources of energy. Therefore, the adequate functioning of the market for natural gas is of great importance to society.

This thesis is concerned with the question of how to structure the natural gas market in such a way that its adequate functioning is guaranteed. Three policy goals are usually distinguished with regard to energy markets: affordability, supply security and sustainability. In the case of natural gas, the former two are the main concern, as the sustainability of our energy system is not affected much by the structure of the natural gas market.

First, the main concepts are defined. The natural gas market is conceptualized as the organization of the natural gas value chain, which is itself a series of seven processes: exploration, production, processing, transport, storage, distribution and consumption. Affordability is simply the market price of natural gas and supply security is a set of three boundary conditions the market must not transgress. Supply must not fall below demand, the amount of gas delivered must not fall below the amount contracted, and the market price must not exceed the maximum acceptable price.

Next, a scan of existing models is performed to see if they are capable of answering the question posed. The main shortcoming of the models analyzed is that their 'perfect market' assumptions prevent them from representing supply insecurity. Therefore, a new modeling framework is developed in which alternative assumptions can be made. This framework is based on the methodology of agent-based computational economics and is called ENETSIM (Energy NETwork SIMulator).

The basis of ENETSIM is a library of eight agents, which can be combined in different ways to form an agent network representing the natural gas market. Five actor agents represent resource operators, network operators, storage operators, traders and consumers respectively. They are connected by three types of institutional agent: a spot market, a bilateral contract and integration. When an agent network is chosen, decision algorithms for each agent and a dataset are added. The simulation model created in this way is a dynamic system evolving in discrete, single day time steps. It yields output describing both the individual behavior of agents and the affordability and supply security of the market as a whole.

Initially, the functioning of this framework is explored in a series of basic models. It is concluded from the results obtained that the framework can be used fruitfully to analyze the affordability and supply security associated with different market structures. In addition, a modification of the framework is presented which enables its use in an educational game.

Next, the methodology is employed to study the liberalization process of the Dutch natural gas market. Two models are constructed, representing the structure of the Dutch market before and after liberalization. Liberalization is shown to have limited potential for improving affordability, while introducing some novel risks to supply security.

Finally, a scenario study is performed to explore the future of the Dutch natural gas market. Three scenarios are developed, investigating the implications of three currently observable trends: the transition to a sustainable energy system, the integration of national markets into a single European market, and the changes in company behavior in response to the liberalized environment. The impact of these developments on policy goals is shown to be substantial. While their effect on affordability is often direct and permanent, their effect on supply security depends crucially on the speed and magnitude of the changes taking place, and is mostly temporary.

The main conclusions which can be drawn from this thesis are the following. First, the modeling framework created for this study has provided a way to link the design of natural gas policy to market performance via the behavior of individual companies. In addition, it combines the analysis of affordability and supply security in a single framework, and incorporates time-dependent, out-of-equilibrium phenomena. Simulations performed using this framework have revealed several tradeoffs between affordability and supply security which were absent from previous models.

This study has also demonstrated that the liberalized market is a complex system, which requires skillful management from policy makers. Fundamental changes to this system have the potential to destabilize the market and to threaten supply security. Therefore, policy makers would be well-advised to develop a more integrated vision of energy policy, taking into account the effect each policy has on all policy goals, rather than just one.

The further development of the modeling framework could proceed by expanding model scope. Fixed properties can be made variable. For example, the shape of the agent network could be allowed to change during the course of a simulation. Furthermore, additional empirically observed phenomena can be incorporated in the framework, such as mergers and acquisitions. Finally, additional performance indicators can be added to model output, starting with a measure for sustainability.

Nederlandse samenvatting

Aardgas is een mengsel van koolwaterstoffen, voornamelijk methaan, dat in de natuur gevonden wordt. Het voorziet in een aanzienlijk deel van onze energiebehoefte. Het is dan ook essentieel voor onze huidige energie-intensieve samenleving dat de markt voor aardgas goed functioneert. Dit proefschrift heeft tot onderwerp hoe de aardgasmarkt moet worden vormgegeven om dit te bereiken. De overheid hanteert drie criteria voor het goed functioneren van energiemarkten: betaalbaarheid, betrouwbaarheid en duurzaamheid. Voor de aardgasmarkt zijn met name de eerste twee van belang. De betaalbaarheid van aardgas komt tot uitdrukking in de prijs, de betrouwbaarheid in de continue levering van voldoende aardgas.

Bestaande modellen van de aardgasmarkt gaan uit van een continu evenwicht in de markt tussen vraag en aanbod en zijn daarom niet geschikt om betrouwbaarheidsvraagstukken te analyseren. Daarom is voor deze studie een nieuw modelleerraamwerk ontwikkeld, ENETSIM (Energy NETwork SIMulator), waarbinnen betaalbaarheid en betrouwbaarheid in samenhang onderzocht kunnen worden. Het uitgangspunt van de gebruikte methode (agent-based computational economics) is om individuele partijen en hun locale interacties te modelleren. Het gedrag van de markt als geheel is de resultante van deze interacties. In deze studie zijn vijf soorten partijen meegenomen: de producent, de handelaar, de transporteur, de opslagaanbieder en de eindgebruiker. Deze partijen interacteren door onderling contracten af te sluiten, met elkaar te handelen op de gasbeurs, of samen een bedrijf te vormen. Hun gezamenlijke gedrag bepaalt uiteindelijk de betaalbaarheid en de betrouwbaarheid van de aardgasvoorziening.

Met behulp van dit raamwerk zijn eerst enkele eenvoudige modellen gemaakt om de methode te valideren. Ook zijn de mogelijkheden voor het gebruik van de methode in educatief spelverband verkend. Daarna zijn twee modellen gebouwd om het functioneren van de Nederlandse aardgasmarkt voor en na liberalisering te vergelijken. Ten slotte zijn enkele toekomstscenario's ontwikkeld voor de Nederlandse aardgasvoorziening. Hierin zijn de effecten onderzocht van trends zoals de transitie naar een duurzame energievoorziening, de integratie van Europese energiemarkten en het veranderende gedrag van marktpartijen als gevolg van de liberalisering.

Op basis van deze analyses is geconcludeerd dat:
1) Het ENETSIM-raamwerk goed functioneert, en daarmee geschikt is om betaalbaarheid en betrouwbaarheid in samenhang te analyseren. Op deze manier kunnen ook conflicten tussen de beide doelen zichtbaar gemaakt worden.
2) Liberalisering een beperkt effect heeft op de betaalbaarheid van aardgas, maar de betrouwbaarheid vermindert.
3) Veranderingen in de aardgasmarkt zorgvuldig gestuurd moeten worden om de betrouwbaarheid te garanderen. Gevolgen voor de betaalbaarheid zijn vaak direct zichtbaar en permanent aanwezig, terwijl gevolgen voor de betrouwbaarheid sterk

afhankelijk zijn van de grootte en snelheid van de verandering en vaak tijdelijk van aard zijn.
4) De geliberaliseerde aardgasmarkt een complex systeem is en dat een adequate vormgeving van de markt een samenhangende visie van beleidsmakers vereist op alle beleidsdoelen in samenhang met elkaar.

Verdere ontwikkeling van het raamwerk is gewenst. Enkele zaken die nu van buitenaf aan een model worden opgelegd zouden er integraal deel van uit kunnen maken; sommige in de markt waargenomen fenomenen kunnen nog niet binnen het raamwerk gesimuleerd worden; ten slotte zou het functioneren van de aardgasmarkt geanalyseerd kunnen worden met betrekking tot additionele beleidsdoelen.

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Curriculum Vitae

Menno van Benthem werd geboren op 5 maart 1979 in Rotterdam. Hij behaalde in 1997 zijn gymnasiumdiploma aan het Rotterdams Montessori Lyceum. Aansluitend volgde hij de studie Natuurwetenschappen en Bedrijf en Bestuur aan de Universiteit Utrecht. In 1998 behaalde hij zijn propedeuse en koos vervolgens voor een economisch-natuurwetenschappelijke specialisatie. Als onderdeel van zijn studie liep hij stage bij de ABN Amro, waar hij onderzoek deed naar fusies en overnames in de chemische industrie. In het kader van een cultureel uitwisselingsproject liep hij stage in Turkije bij een lokale producent van verpakkingsmaterialen, waar hij marktonderzoek verrichtte en contacten legde met buitenlandse klanten. Zijn afstudeerstage vond plaats bij TNO, waar hij onderzoek deed naar voorzieningszekerheid in de Nederlandse aardgassector. In 2004 studeerde hij met genoegen af. Voor zijn scriptie won hij een prijs van de Nederlandse aardgasindustrie. In 2005 begon hij als promovendus bij de Rijksuniversiteit Groningen, waar hij in samenwerking met TNO zijn onderzoek naar de aardgasmarkt voortzette. Naast zijn onderzoek was hij gastdocent bij drie master-opleidingen en werkte hij mee aan verschillende projecten bij TNO. Sinds mei 2009 is hij werkzaam bij E.ON Benelux als portfolio manager gas.